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Title: Comparison of Background Radiation Effective Dose Rates for Residents in the Vicinity of a Research and Nuclear Weapons Laboratory (Los Alamos County, USA) with National Averages

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Comparison of background radiation effective dose rates for residents in the vicinity of a research and nuclear weapons laboratory (Los Alamos County, USA) with national averages

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Abstract

Los Alamos National Laboratory (LANL or the Laboratory) is a research and nuclear weapons facility in north-central New Mexico (Los Alamos County). Workers at LANL, who generally live in the vicinity of the facility, receive radiation doses from naturally occurring sources and may also be exposed to occupational radiation sources and emissions from the Laboratory. Radiation doses from occupational and LANL emissions are carefully measured; however, background doses to residents are often estimated from national averages even though they can vary widely based on site and individual-specific parameters. Accurate estimation of naturally occurring background radiation dose and its variation is important to evaluating for potential health effects to workers or residents resulting from LANL operations.

Here we assess naturally occurring sources of radiation exposure including cosmic and cosmogenic radiation sources as well as primordial terrestrial sources. Additionally, we evaluate the average effective background dose to individuals in Los Alamos County from anthropogenic or "man-made" sources including medical procedures, industrial activities, and consumer products. A 2009 report by the National Council on Radiation Protection and Measurements (NCRP 160) compiled information on exposures to all of these sources and provided an average annual effective dose to an individual resident of the United States of 6.2 $\frac{\mathrm{mSv}}{\mathrm{y}}$. Compilation of site-specific data allowed for a local revision of this value to 8.2 $\frac{\mathrm{mSv}}{\mathrm{y}}$ for residents of Los Alamos County.

Introduction

Humans are continually exposed to ionizing radiation from a wide variety of sources. Reports by the National Council on Radiation Protection and Measurements (NCRP) detail sources and average levels of background radiation exposure for the population of the United States and provide information on the variability of the doses that might cause radiation dose levels for any subpopulation to deviate from the average (NCRP, 1987a) (NCRP, 1987b) (NCRP, 2009). Additional exploration of background radiation levels has been conducted by the United Nations Scientific Council on the Effects of Atomic Radiation (UNSCEAR), as described in its report (UNSCEAR, 2000). The purpose of the following assessment was to characterize the background radiation exposure of a representative individual living in Los Alamos County (E_{LA}) and to then contrast this exposure with average dose levels for a representative individual in the United States (E_{US}).

Background radiation dose is the sum of the individual's exposure to the following sources: cosmic and cosmogenic, external terrestrial, inhalation of radioactive aerosol or gas, ingestion of water or foodstuffs containing naturally occurring radioactive materials, fallout from nuclear weapons testing, use of radioactive consumer products or activities, emissions from nuclear facilities, and diagnostic or therapeutic radiological medicine procedures. Factors associated with exposure locations (e.g. altitude, latitude, local geology, radon concentrations in basements) and personal experiences (e.g. fraction of time spent indoors, sources of various foods and water, and medical procedures) drive the variability in individual exposures.

Because of the large variability in these factors, assessment of background radiation exposure for local representative individuals can be valuable for health risk assessments for local populations and for epidemiology studies. Background radiation dose assessment is particularly valuable for risk assessments at sites such as Los Alamos County, where people have the potential to receive occupational radiation doses as a result of working in a nuclear industry as well as environmental radiation doses due to past and present radioactive emissions.

Cosmic and Cosmogenic Sources

Cosmic radiation consists of photons and nucleons (particularly protons) that impinge on the earth's atmosphere with a flux that varies spatially and temporally (Heinrich, Roesler, & Schraube, 1999). These primary protons smash into the gas of the atmosphere and cause a cascade of secondary nuclear spallation products that can penetrate to ground levels. Secondary particles include elements with low Z numbers (e.g. those having fewer protons than nitrogen and oxygen), muons, photons, neutrons, and electrons. Spallation, as well as activation of atmospheric molecules, can also form "cosmogenic" nuclides that are radioactive and decay with unique half-lives.

The flux of secondary ionizing radiations decreases at lower altitudes due to more shielding from the thicker atmospheric layer. An overall depiction of this variation with altitude is presented in Figure 1. Cosmic ray dose rate also varies with solar activity and latitude (due to variations in the earth's geomagnetic field).

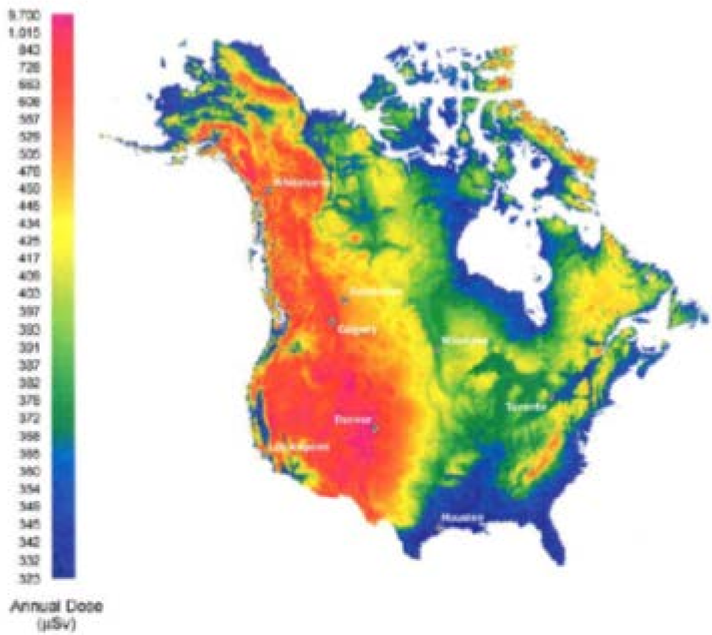

Figure 1: Cosmic radiation doses $\frac{\mu Sv}{y}$ in North America generated using CARI-6 calculations (NCRP, 2009, p. 34 Figure 3.4)

Calculating cosmic ray dose estimates involves consideration of not only altitude (Los Alamos elevation is ~ 2200 m), but also time spent indoors and shielding from building materials, though these materials provide only partial shielding. For example, about 40% of the estimated dose at 2200 m is from muons, which can penetrate a meter of lead shielding (UNSCEAR, 2000). UNSCEAR has reported on the effect of structural shielding, indicating that observed correction factors "ranged from close to 1 for… a small wooden house, to 0.4 for lower storeys (sic) of substantial concrete buildings" (2000, p. 87 Annex B paragraph 28). This report also indicates that a housing factor of 0.8 (later used by NCRP 160) is appropriate. Finally, the average individual is estimated to spend 80% of his or her time indoors (UNSCEAR, 2000, p. 87 Annex B paragraph 30). NCRP 160 split this value by age range, finding that adults > 18 y spend 15% of their time outdoors (85% indoors) (2009, p. 32 Table 3.2). Finally, the neutron component of cosmic ray dose may be as much as 25% of the total (O'Brien & Skalski, 1996). Neutron dose rates are not easy to measure, especially because the dosimetry of very high energy cosmic neutrons is not well understood.

As an estimate of cosmic ray dose, NCRP Report 160 found a population-weighted average annual effective dose corrected for shielding and time spent indoors of 0.33 $\frac{\mathrm{mSv}}{\mathrm{y}}$ (ranging from 0.28 $\frac{\mathrm{mSv}}{\mathrm{y}}$ in Hawaii to 0.82 $\frac{\mathrm{mSv}}{\mathrm{y}}$ in Colorado Springs, CO) (NCRP, 2009, p. 31). This range compares to those published previously in NCRP Report 94, which provided an altitude-averaged value of 0.27 $\frac{\mathrm{mSv}}{\mathrm{y}}$ and a range from 0.24 $\frac{\mathrm{mSv}}{\mathrm{y}}$ at sea level to 1.25 $\frac{\mathrm{mSv}}{\mathrm{y}}$ in Leadville, CO (3,200 m) (NCRP, 1987b).

Additional cosmic radiation exposure occurs during aircraft flights, the magnitude of which depends on the duration and frequency of flights taken by each member of the population. These brief periods at very high elevations can contribute significantly to the collective dose. NCRP 160 (2009) included dose from commercial airline flights in its section on consumer products instead of the section on cosmic rays, finding an average dose rate and standard deviation of $3.3 \pm 1.8 \frac{\mu\mathrm{Sv}}{\mathrm{air\ hour}}$ for domestic flights and $5.2 \pm 0.9 \frac{\mu\mathrm{Sv}}{\mathrm{air\ hour}}$ for international flights.

Cosmogenic radionuclides are created as activation products or as spallation products from collisions of cosmic nucleons with atmospheric gas. The primary cosmogenic radionuclides that contribute to radiation dose are ^{3}H, ^{14}C, ^{22}Na, and ^{7}Be. Effective dose rates from cosmogenic radionuclides vary due to altitude, latitude, and season, similar to cosmic radiation, but the overall doses associated with these radionuclides (~ 0.01 $\frac{\mathrm{mSv}}{\mathrm{y}}$) are relatively small (NCRP, 2009, p. 74) (UNSCEAR, 2000, p. 89).

Terrestrial Sources (External and Internal)

Radiation doses from terrestrial radiation sources are primarily due to primordial radionuclides such as ^{238}U, ^{235}U, ^{232}Th, and ^{40}K and the radioactive progeny in their respective decay chains. The dose pathways from these radionuclides include external irradiation, inhalation, and ingestion of food and water that contain these radionuclides. For ubiquitous background exposure, radon and progeny are the primary contributors to effective dose (E_{US}) for the average resident (73%), with cosmic (11%) and terrestrial external (7%) contributing the next largest fractions. Internal exposures to potassium, thorium, and uranium series also contribute (collectively 9%) (NCRP, 2009, p. 77 Figure 3.19).

Because the concentrations of primordial radionuclides can vary dramatically due to local geology, the effective dose rates in Los Alamos County from terrestrial radiation could be expected to differ from US averages. In particular, local uranium and potassium concentrations would be expected to be higher than concentrations in the United States and worldwide because Los Alamos is situated in a mountainous region with past volcanic activity (USGS, 1993). Appendix I provides false color plots of the spatial distributions of uranium, thorium, and potassium in the United States. Because of the scale of these maps, it is worthwhile to note that local variation can be significant even within the individual 10 km by 10 km pixels that make up the image.

External

The external terrestrial dose rate is primarily due to penetrating gamma radiation from the primordial nuclide decay chains contained in surrounding rocks and soils. This dose is a function of the combined soil concentrations and can be generally described by the map in Figure 2. External doses from the combined ^{238}U, ^{232}Th, and ^{40}K are discussed. Note: the contribution to external dose rate from ^{235}U is only about 1% of that from ^{238}U due to lower natural activity and fewer, lower energy gammas in the ^{235}U series.

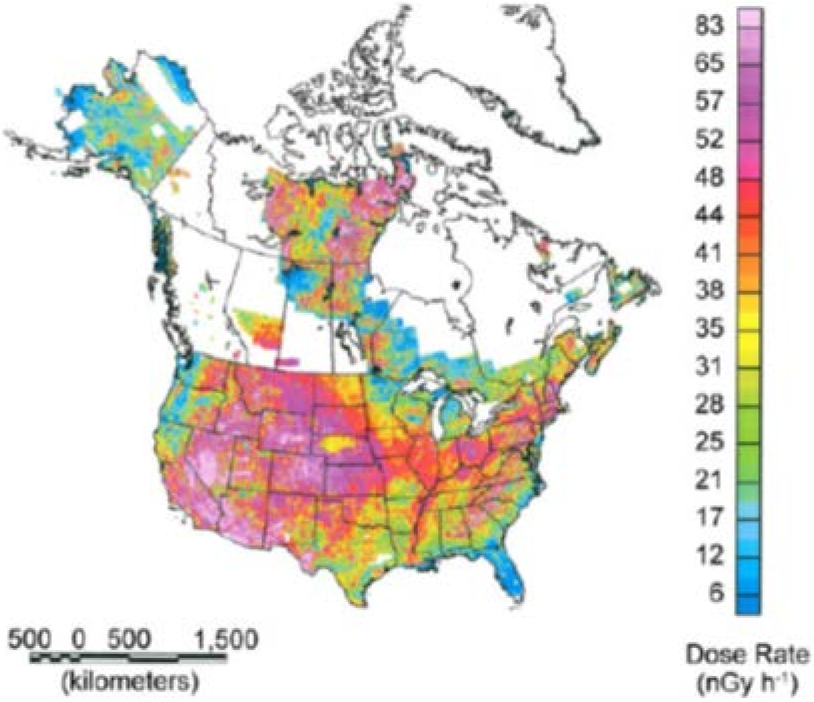

Figure 2: Terrestrial gamma-ray absorbed dose rates in air in North America (NCRP, 2009, p. 42 Figure 3.9)

Reported values for external radiation dose rates from terrestrial sources vary significantly across different areas for several reasons. First, national estimates of terrestrial radiation dose use population weighting of the measured values, which can lower the estimated dose rate because mountainous areas, often with higher-concentrations, are given a small statistical weight. Second, techniques for measuring this component of the radiation field vary and often do not separate out the cosmic component. In many cases, external doses are estimated by measuring external exposure or absorbed dose rate in air, and these values are adjusted for the contribution of cosmic radiation and converted to equivalent doses. Additionally, large grid patterns in aerial surveys can underestimate the effect of localized hotspots. Finally, various structural materials provide a range of shielding levels which reduce the dose from terrestrial radiation, and terrestrial dose rates in cities are reduced by asphalt covering the ground. An indoor-outdoor correction factor (building attenuation factor) can adjust for this variation, but the choice of this factor has varied over time.

Even with these sources of variation, various historical estimates have been relatively consistent, and are included here for reference. The most recent average value ($0.21 \frac{\mathrm{mSv}}{\mathrm{y}}$) provided by NCRP

160 is used for comparison in the discussion. Doses have been reported by various sources as follows:

- 0.28 $\frac{\mathrm{mSv}}{\mathrm{y}}$ average annual gamma-ray effective dose equivalent (range from 0.16 $\frac{\mathrm{mSv}}{\mathrm{y}}$ on the Atlantic and Gulf coastal plains and 0.63 $\frac{\mathrm{mSv}}{\mathrm{y}}$ on the eastern slopes of the Rockies) (NCRP, 1987a)
- 0.28 $\frac{\mathrm{mSv}}{\mathrm{y}}$ population-weighted average dose equivalent rate (range from 0.23 $\frac{\mathrm{mSv}}{\mathrm{y}}$ on the coastal plain to 0.90 $\frac{\mathrm{mSv}}{\mathrm{y}}$ on the Colorado plateau) (NCRP, 1987b)
- 0.29 $\frac{\mathrm{mSv}}{\mathrm{y}}$ (range from 0.09 to 0.72 $\frac{\mathrm{mSv}}{\mathrm{y}}$) using a dose equivalent conversion of 0.7 $\frac{\mathrm{mSv}}{\mathrm{mGy}}$ (UNSCEAR, 2000, p. 117 Table 7)
- 0.21 $\frac{\mathrm{mSv}}{\mathrm{y}}$ population-weighted annual effective dose (range from 0.04 to 0.51 $\frac{\mathrm{mSv}}{\mathrm{y}}$ based on Figure 2 using an effective dose conversion of 0.7 $\frac{\mathrm{mSv}}{\mathrm{mGy}}$), data averaged over 100 km^2 grid pattern (NCRP, 2009, p. 42)

Internal

Internal exposure to terrestrial radionuclides is due to inhalation as well as ingestion of food, water and milk that contains radioactive material. Isotopes of radon, a radioactive gas, occur in both uranium and thorium decay series, and radon infiltration into homes is one of the largest sources of radiation exposure to the United States population with individual effective doses averaging 2.28 $\frac{\mathrm{mSv}}{\mathrm{y}}$ (NCRP, 2009, p. 12). There is substantial variation in radon concentrations throughout the U.S. primarily due to local levels of uranium in the soil and also due to insulation in homes (see Figure 3). The local geology, construction materials, and building designs in Los Alamos County are sufficiently different from United States averages to have justified a radon survey of Los Alamos County residences (Whicker & McNaughton, 2009). Dose from radon progeny also depends on aerosol characteristics as well as personal traits like age, gender, breathing style, and cigarette smoking.

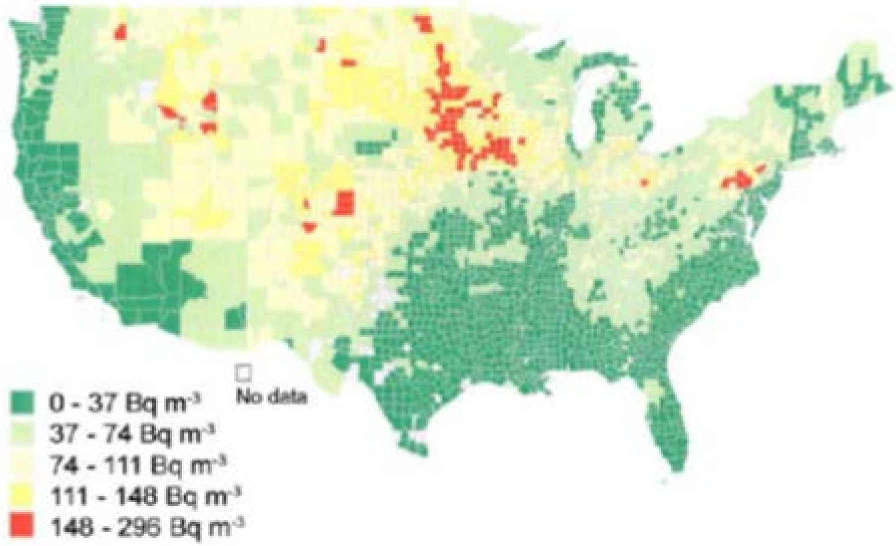

Figure 3: Average radon concentrations in living areas around the United States (NCRP, 2009, p. 53 Figure 3.13)

Ingestion of radionuclides in foodstuffs and water contributes a small fraction of the background dose. Radioactive potassium is present naturally in food, primarily in fruits and vegetables. Doses from ^{40}K vary from 0.12 to 0.15 $\frac{\mathrm{mSv}}{\mathrm{y}}$ based on age and gender, with annual doses to a child estimated at 0.12 $\frac{\mathrm{mSv}}{y}$, adult female at 0.12 $\frac{\mathrm{mSv}}{\mathrm{y}}$, and adult male at 0.15 $\frac{\mathrm{mSv}}{\mathrm{y}}$ (NCRP, 2009, p. 68 Table 3.11). Additionally, uranium and thorium series nuclides are present in food and water, with approximately 39% of the dose coming from domestic water supplies (NCRP, 2009). Doses from uranium and thorium series nuclides (excluding radon doses to the lung) summed to 0.13 $\frac{\mathrm{mSv}}{\mathrm{y}}$ (NCRP, 2009, p. 71 Table 3.12). This report provides a summed value for internal ingestion sources of 0.29 $\frac{\mathrm{mSv}}{\mathrm{y}}$ (NCRP, 2009, p. 12).

Anthropogenic Sources

In addition to exposures from naturally occurring radioactive material, people are also regularly exposed to radiation from a variety of anthropogenic, or man-made, sources.

Medical

The largest source of anthropogenic radiation dose to the public is from radiation-based medical procedures. These procedures use radioactive sources or radiation producing devices for diagnostic (e.g. x-rays) and therapeutic (e.g. cancer treatment) purposes. The use and value of such radiological medical procedures has grown dramatically in recent decades. Of particular interest for radiation dose is the growth in the use of computed tomography (CT) scans. NCRP 160 provided annual rates of increase for CT scans averaging 10% per year (2009, p. 91 Figure 4.1) and predicted a continuing increase over the next ten years. The substantial increase justifies an assessment for Los Alamos County accounting for possible variations in rates of general health of a population by state, age of the study population, and health care insurance coverage, all of which can impact rates of diagnostic and therapeutic radiation-based medical procedures.

While it is possible to calculate a population averaged individual dose in the United States (E_{US}) using nationwide exposure data for medical procedures, the calculated values provide somewhat misleading information, as only those individuals who undergo such medical procedures receive doses. Therefore, average values distributing dose among all individuals are necessarily high for some and low for others. Also, the distribution of doses may be skewed toward older individuals and those of lower health status. Estimated doses from medical procedures in 2006 found a E_{US} of 3 $\frac{\text{mSv}}{\text{y}}$, which was divided into 1.47 $\frac{\text{mSv}}{\text{y}}$ for CT scans, 0.77 $\frac{\text{mSv}}{\text{y}}$ for nuclear medicine, 0.43 $\frac{\text{mSv}}{\text{y}}$ for interventional fluoroscopy, and 0.33 $\frac{\text{mSv}}{\text{y}}$ for conventional radiography and fluoroscopy. Another subcategory, external-beam radiotherapy, had a E_{US} of 1.2 $\frac{\text{mSv}}{\text{y}}$ but was excluded from the total because the exposure population was small and consisted of patients being treated for life-threatening illnesses (NCRP, 2009). These values are primarily helpful for determining the relative contributions to medical radiation dose in the United States.

A later study in 2009 looked at medical radiation doses in 952,420 adults ages 18-64 (Fazel, et al.). This study found that 68.8% of all enrollees in five different healthcare markets underwent at least one imaging procedure. Overall, the mean cumulative effective dose was 2.4 $\frac{\text{mSv}}{\text{y}}$ with a standard deviation of 6 $\frac{\text{mSv}}{\text{y}}$. The distribution of doses was wide, with the median (0.1 $\frac{\text{mSv}}{\text{y}}$) and interquartile range (0.0-1.7$\frac{\text{mSv}}{\text{y}}$) of the doses being below the mean. The 95th percentile listed for this study population was 12.3$\frac{\text{mSv}}{\text{y}}$, and it was noted by the authors that cumulative effective doses were higher for older individuals and higher for women compared to men. The study also stratified subjects by dose received, finding that 79% received doses $\leq 3\,\frac{\mathrm{mSv}}{\mathrm{y}}$, 19% received doses between 3 and 20 $\frac{\mathrm{mSv}}{\mathrm{y}}$, about 2% received doses between 20 and 50 $\frac{\mathrm{mSv}}{\mathrm{y}}$, and only 0.2% received doses > 50 $\frac{\mathrm{mSv}}{\mathrm{y}}$ (Fazel, et al., 2009).

Fallout

Global fallout from nuclear weapons testing in the 1950s and 1960s injected substantial amounts of radioactive debris into the atmosphere that circulated globally but the concentrations were greatest in the northern hemisphere (Hardy, Krey, & Volchok, 1973). Deposition of these radionuclides resulted in measureable levels of contamination.

Early after the detonations, shorter-lived radionuclides like ^{131}I were the primary contributors to public radiation doses, but longer-lived radionuclides such as ^{3}H, ^{137}Cs, ^{90}Sr, and $^{239/240}$Pu continue to contribute doses today. The annual amount of radiation dose from fallout is generally related to the amount of precipitation in the area (Whicker & Schultz, 1982). Annual precipitation in New Mexico is about 350 mm (U.S. Department of the Interior & USGS, 2005), but is higher in Los Alamos, which sits on the western flank of the Jemez Mountains at an elevation of about 2225 m with an average precipitation of about 500 mm per year in the town, and more closer to the mountains. Concentrations of fallout radionuclides vary by more than an order of magnitude for several reasons: the rainfall is higher closer to the mountains, fallout is concentrated in the ash remaining after forest fires, and runoff accumulates in low-lying areas.

Despite the variation in global fallout amounts by location, overall this anthropogenic source contributes less than 1% of a person's overall radiation dose (fairly constant at < 0.01 $\frac{\mathrm{mSv}}{\mathrm{y}}$) (UNSCEAR, 2000). Fallout nuclides can be identified in environmental samples at LANL, thus they have been investigated as a potential source of background exposure

Consumer Products

Similarly, some consumer products and activities contain radioactive materials. The E_{US} to individuals from use of consumer products was 0.13 $\frac{\mathrm{mSv}}{\mathrm{y}}$ (NCRP, 2009), which was primarily due to cigarette smoking (35%), followed by building materials (27%) and commercial air travel (26%) (NCRP, 2009, p. 185 Figure 5.1).

Industrial Activities & Other Anthropogenic Exposures

Naturally occurring radionuclides can contribute to dose when materials which contain them are recovered, processed, used or released. Processes like mineral recovery and fossil fuel combustion can release or concentrate these nuclides, increasing doses to workers or the public. The UNSCEAR Annex B (2000) notes that some members of the public could receive doses on the order of 0.1 $\frac{\mathrm{mSv}}{\mathrm{y}}$ from these sources, but doses would more likely be 0.001 to 0.01 $\frac{\mathrm{mSv}}{\mathrm{y}}$ for most of those exposed. Nuclear power generation, DOE installations, industrial, medical, educational, security and research activities can contribute dose to those nearby. NCRP 160 provided a summed E_{US} of 0.003 $\frac{\mathrm{mSv}}{\mathrm{y}}$ for industrial, security, medical, educational, and research uses of radiation (2009). Of this exposure, the largest contribution was secondary exposure to nuclear medicine patients (72%). On a nationwide scale, DOE installations contribute less than 1% of the NCRP 160 dose from industrial and research activities.

Occupational sources of radiation exposure are generally less than 0.1% of the average person's overall radiation dose. For example, the population-averaged E_{US} from occupational sources was 0.005 $\frac{\mathrm{mSv}}{\mathrm{y}}$ (NCRP, 2009). This effective dose rate is attributed primarily to workers in medical and aviation fields, with smaller fractions of the collective effective dose from other industries including commercial nuclear power and DOE sites. As with medical exposures, the dose contribution to E_{US} is only from exposed workers. This value is expected to underestimate the exposure to radiation workers and overestimate the exposure to the rest of the population.

Methods

The background dose assessment for residents of Los Alamos used a combination of measurements, model results, and literature reviews. Doses for each section were evaluated using site-specific parameters.

Cosmic Radiation

The cosmic component of the radiation background dose was approached using several methods. First, the following equation by Bouville and Lowder (1988) was used to calculate a dose rate ($\dot{H}$) in $\frac{\mu\text{rem}}{\text{h}}$ as a function of the altitude (*z)* in km:

Equation 1

$$\dot{H} = 3.2[0.21e^{-1.649z} + 0.79e^{0.4528z}]$$

Note: 1 $\frac{\mu\text{rem}}{\text{h}} = 0.01\ \frac{\mu\text{Sv}}{\text{h}} = 88\ \frac{\mu\text{Sv}}{\text{y}} = 0.088\frac{\text{mSv}}{\text{y}}$

This equation has been used in many LANL papers and annual site environmental reports (ASERs) to estimate cosmic radiation dose rates. The equation does not consider cosmic ray dose rate due to neutrons, and 0.27 $\frac{\text{mSv}}{\text{y}}$ (3.2 $\frac{\mu\text{rem}}{\text{h}}$) at sea level is the cosmic ray dose to which the equation is normalized. This value comes from NCRP 94 (1987b) and is a population and altitude averaged annual dose equivalent including the contribution from air travel and adjusted using a housing factor of 0.8 to represent indoor values.

Cosmic ray dose rates were also investigated using the program CARI-6 (Federal Aviation Administration, 2012). This program returns effective dose rates using the tissue weighting factors from ICRP 60, and neutron dose accounts for approximately 25% of the total dose (O'Brien & Skalski, 1996). Input values were adjusted using Los Alamos County locations and elevations. An important consideration in use of the CARI-6 software is that cosmic ray intensity varies significantly over time. The intensity, and therefore the dose, varies inversely with solar activity over the 11 year solar activity cycle. Therefore, doses were averaged over an 11 year period. Concerning the choice of a housing factor, the 20% reduction (housing factor of 0.8 consistent with NCRP and UNSCEAR reports) was used. Note: Los Alamos homes and workplaces are frequently single story buildings with lighter roofing materials, indicating that the 20% reduction factor might overestimate the amount of shielding, resulting in a lower dose than is truly received. Weighted totals were calculated by assuming 80% of an individual's time was spent indoors (UNSCEAR, 2000).

Measurements of external dose have also been made in Los Alamos by the Direct Penetrating Radiation Monitoring Network (DPRNET), the Neighborhood Environmental Watch Network (NEWNET), and aerial flyover studies. Because external dose is inherently comprised of both external terrestrial radiation and cosmic radiation, DPRNET and NEWNET data report a combined background external gamma ray dose rate. Reuter Stokes data (Figure 4) were used to separate the cosmic and terrestrial dose components in the aerial flyover studies.

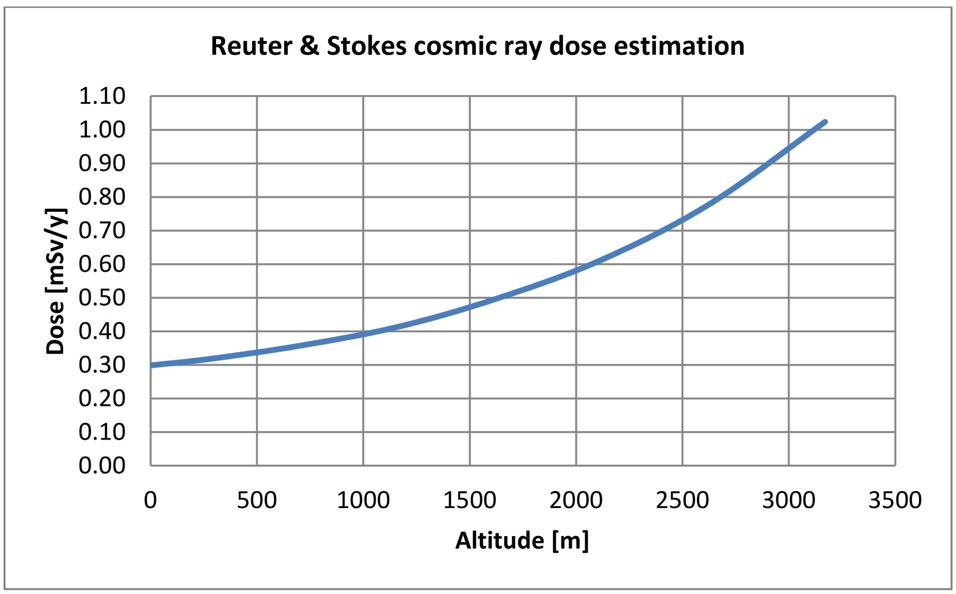

Figure 4: Cosmic ray response of an ionization chamber from Table 2.2 in the Reuter Stokes manual. This figure was used as a nominal non-terrestrial background count rate for correction of aerial flyover data based on altitude.

Terrestrial Radiation

External

Estimates of terrestrial dose rates in the Los Alamos region were based on 1) measurements of concentrations of naturally occurring radioactive material in local soils and 2) exposure rate measurements including DPRNET, NEWNET, and aerial flyover studies. These data have been cross-calibrated and compared with international inter-comparisons (LANL, 2006) (McNaughton M. , n.d.) (DOE, 2012).

Measurements of soil ^{238}U, ^{232}Th, and ^{40}K series were used to find a value for E_{LA} as described in Equation 2 and Equation 3. The estimated dose rate to air ($\dot{D}_{\mathrm{air}}$) in units of $\frac{\mathrm{nGy}}{\mathrm{h}}$ can be calculated from terrestrial radiation concentrations $\left[\frac{\mathrm{Bq}}{\mathrm{kg}}\right]$ using dose rate conversion coefficients $\left[\frac{\mathrm{nGy}}{\mathrm{h}}\left(\frac{\mathrm{Bq}}{\mathrm{kg}}\right)^{-1}\right]$ (Saito & Jacob, 1995) (UNSCEAR, 2000, p. 116 Annex B) (NCRP, 2009, p. 37). The annual effective dose (AED) $\left[\frac{\mathrm{mSv}}{\mathrm{y}}\right]$ is calculated using an effective dose conversion factor of $0.7\,\frac{\mathrm{mSv}}{\mathrm{mGy}}$.

Equation 2

$$\dot{D}_{\mathrm{air}} = C_{\mathrm{U-238}}(0.463) + C_{\mathrm{Th-232}}(0.604) + C_{\mathrm{K-40}}(0.0417)$$

Equation 3

$$AED = \dot{D}_{\mathrm{air}}\left[\frac{\mathrm{nGy}}{\mathrm{h}}\right] \times 8760\,\frac{\mathrm{h}}{\mathrm{y}} \times \frac{10^{-6}\mathrm{mGy}}{\mathrm{nGy}} \times 0.7\,\frac{\mathrm{mSv}}{\mathrm{mGy}}$$

Alternatively, the DPRNET program uses Model 8823 thermoluminescent dosimeters (TLDs) to estimate direct penetrating radiation dose (LANL, 2002). These detectors respond to charged particles, gamma rays, and neutrons. However, due to the short range of charged particles in air, these particles are rarely seen. While cosmic radiation is recorded in these detectors, no subtraction takes place in the reported data. In this report, DPRNET data have been adjusted to account for cosmic radiation by subtracting the cosmic component as estimated by the CARI-6 code.

The NEWNET program measures an exposure rate $\left[\frac{\mu\mathrm{R}}{\mathrm{h}}\right]$ in air which is converted to a deep dose rate using the conversion factor$\left[0.0096\,\frac{\mathrm{Gy}_{\mathrm{tissue}}}{\mathrm{R}}\right]$. These detectors also respond to cosmic radiation, and the typical output does not differentiate between terrestrial and cosmic doses. For this report, NEWNET data have also been adjusted to account for cosmic radiation by subtracting the CARI-6 cosmic estimation.

Aerial flyover studies were conducted at LANL in 1994 and again in 2012 (DOE, 2012). Results of these surveys are derived and recorded using maps of exposure rates $\left[\frac{\mathrm{mR}}{\mathrm{h}}\right]$ at 1 m above ground level. To correct for non-terrestrial background (including cosmic ray dose), results in the aerial flyover studies used data from flying over water (small terrestrial component), flying over a test line, and performing an altitude profile (DOE, 2012).

Internal

To estimate natural inhaled radiation doses, radon concentrations were measured in homes in Los Alamos County. Indoor radon levels were determined in homes which were randomly selected using the phonebook. A questionnaire was distributed to participants and track-etch detectors were placed in homes over three-month sample times. Dose calculations were conducted using the measured radon concentrations, the UNSCEAR 2000 dose conversion factor of $9\,\frac{\mathrm{nSv}}{\mathrm{h}}/\frac{\mathrm{Bq}}{\mathrm{m}^3}$, an equilibrium factor of 0.4, and a seasonal correction factor based on the time of year the measurements were taken. Doses calculated in this study were provided for office worker and more homebound individuals using an office work time of 2,000 h, a home time for the office worker of 5,746 h, and a total time at home for the homebound individual of 7,446 h per year.

Dose from ingestion of foodstuffs was maintained from NCRP 160 due to a lack of complete information. However, some material is provided based on measurements in foodstuffs, literature searches, and drinking water data from Los Alamos County water quality reports and Environmental Protection Agency (EPA) Maximum Contaminant Level (MCL) guidelines.

Anthropogenic Radiation

Medical

Medical exposures to the Los Alamos County population were obtained from the NCRP 160 report. However, some information on local demographics was collected for potential future use. Various factors potentially affecting medical exposures for county residents were considered including age of the population, health coverage, medical usage rates in New Mexico, and procedure rates (Hawkley & Whicker). Computed tomography (CT) scans, conventional radiography and fluoroscopy, interventional fluoroscopy, and nuclear medicine were investigated by NCRP 160, and values of effective dose were provided as follows: CT scan doses in Table 4.2 p. 88, conventional radiography and fluoroscopy in Table 4.7 p. 99, diagnostic and interventional fluoroscopy in Table 4.9 p. 110, and nuclear medicine doses per procedure in Table D.5 p. 284. External beam radiotherapy (EBRT) dose estimates were available in Table 4.17 p. 139 for typical treatment doses, beam energies, and field sizes, but the NCRP report noted that uncertainties on these values were greater than the estimates.

Fallout

Radiation doses from fallout were based on literature values and investigated with regional soil measurements. RESRAD trials using site-specific parameters were conducted to compare Los Alamos effective doses from fallout with the published literature.

Consumer Products

The value of 0.13 $\frac{\mathrm{mSv}}{\mathrm{y}}$ found in NCRP 160 for consumer products was largely unchanged. However, because cigarette smoking contributed 35% of the collective effective dose, this value was adjusted to account for the lower smoking rate of the Los Alamos County population. Radionuclides in smoke that contribute to dose include ^{226}Ra, ^{228}Ra, ^{210}Pb, and ^{210}Po, and the overall annual dose for smoking one cigarette per day is 18 µSv (NCRP, 2009).

Industrial Activities & Other Anthropogenic Exposures

Due to a lack of additional information, the NCRP 160 value of 0.003 $\frac{\mathrm{mSv}}{\mathrm{y}}$ for industrial, security, medical, educational, and research uses of radiation was retained. Because DOE installations contribute less than 1% of this value according to NCRP 160, it was assumed that any additional exposures from LANL (calculated in the following section) could be added to this value. Occupational exposures included in NCRP 160 were subtracted from the total to provide information for comparison of background exposures only.

Results

Cosmic Radiation Dose

Effective dose rates from cosmic radiation in Los Alamos County (E_{LA}) are higher than average effective dose rates in the United States (E_{US}) because of the elevation (2225 m in downtown Los Alamos). Based on the elevation range of Los Alamos County, the predicted dose to residents from NCRP 160 would be between 0.6 and 1.0 $\frac{\mathrm{mSv}}{\mathrm{y}}$ (NCRP, 2009). Of this total, the dose rate from cosmic ray neutrons is estimated to be 0.088 $\frac{\mathrm{mSv}}{\mathrm{y}}$ $\left(1\ \frac{\mathrm{\mu rem}}{\mathrm{h}}\right)$ at sea level and 0.18 $\frac{\mathrm{mSv}}{\mathrm{y}}$ $\left(2\ \frac{\mathrm{\mu rem}}{\mathrm{h}}\right)$ at an altitude of 2 km. Linear extrapolation of this estimate yields 0.19 $\frac{\mathrm{mSv}}{\mathrm{y}}$ from neutrons at 2225 m. Knowing the neutron component is important because the field measurements (e.g., NEWNET and DPRNET) are either insensitive to neutrons (NEWNET) or are calibrated to lower-energy neutrons (DPRNET).

Locally, Bouville and Lowder (1988) found a range between 0.5 and 0.9 $\frac{\mathrm{mSv}}{\mathrm{y}}$ between the Rio Grande and western Los Alamos. Use of the Bouville and Lowder equation (plotted in Figure 5) found a dose rate of 0.6 $\frac{\mathrm{mSv}}{\mathrm{y}}$ for 2225 m. This dose does not include neutrons and incorporates a housing factor of 0.8. Similarly, use of the manual provided by Reuter and Stokes found a dose rate of 0.66 $\frac{\mathrm{mSv}}{\mathrm{y}}$ for 2225 m.

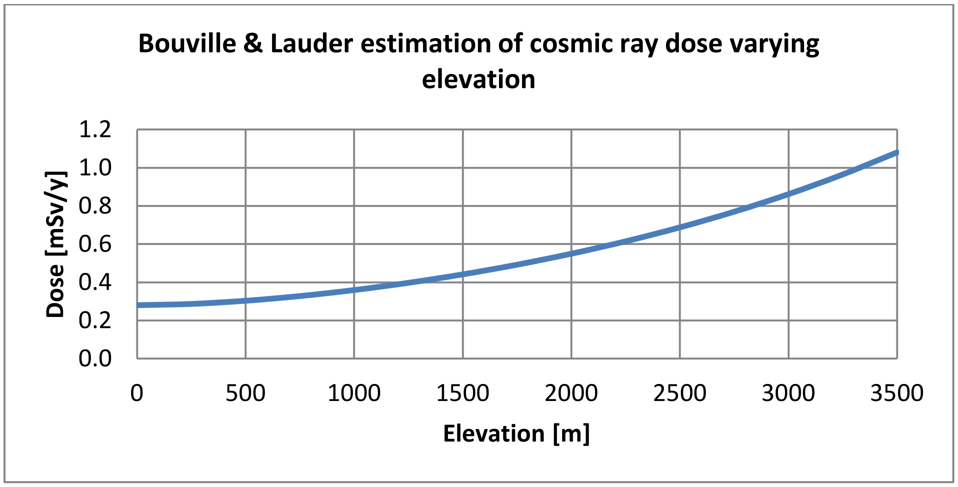

Figure 5: Graph of estimated cosmic ray dose rates obtained using the equation above (Bouville & Lowder, 1988)

Alternatively, cosmic ray dose rates in Los Alamos County varied from 0.71 to 0.93 $\frac{\text{mSv}}{\text{y}}$ based on elevation variation in CARI-6 calculations for 2013 (see Figure 6).

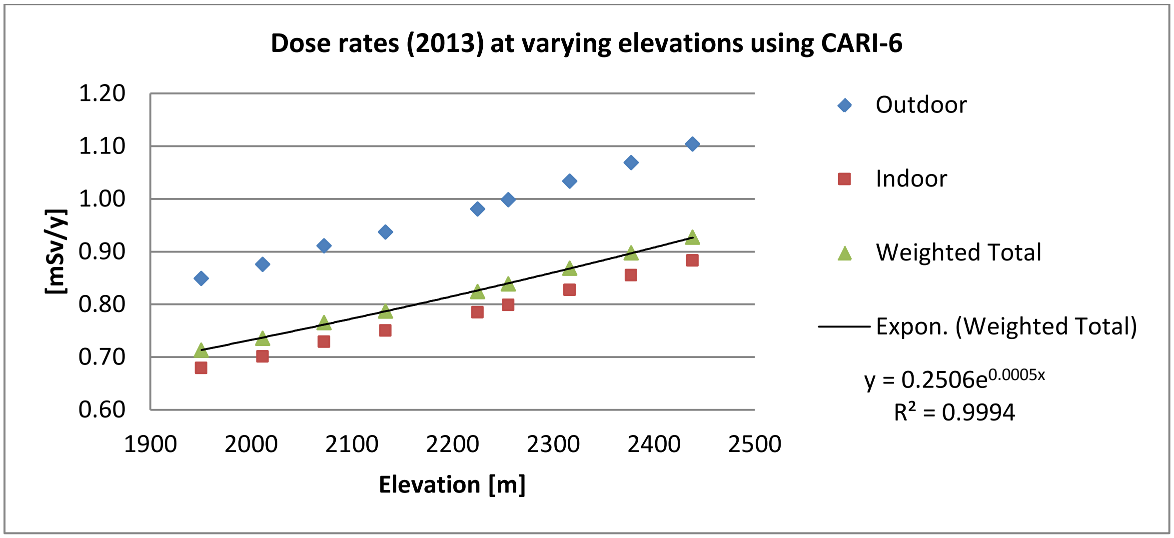

Figure 6: Dose rate from cosmic radiation as a function of elevation incorporating a housing factor of 0.8 and 80% time spent indoors. An exponential trend line is plotted for the weighted total. Reference location is 35° N, 106° W (Federal Aviation Administration, 2012)

A comparison of dose rates for specific locations (forming an elevation profile of Los Alamos County) shows the site-specific variation, indicating that each individual could experience a highly variable cosmic radiation dose throughout the year (see Figure 7).

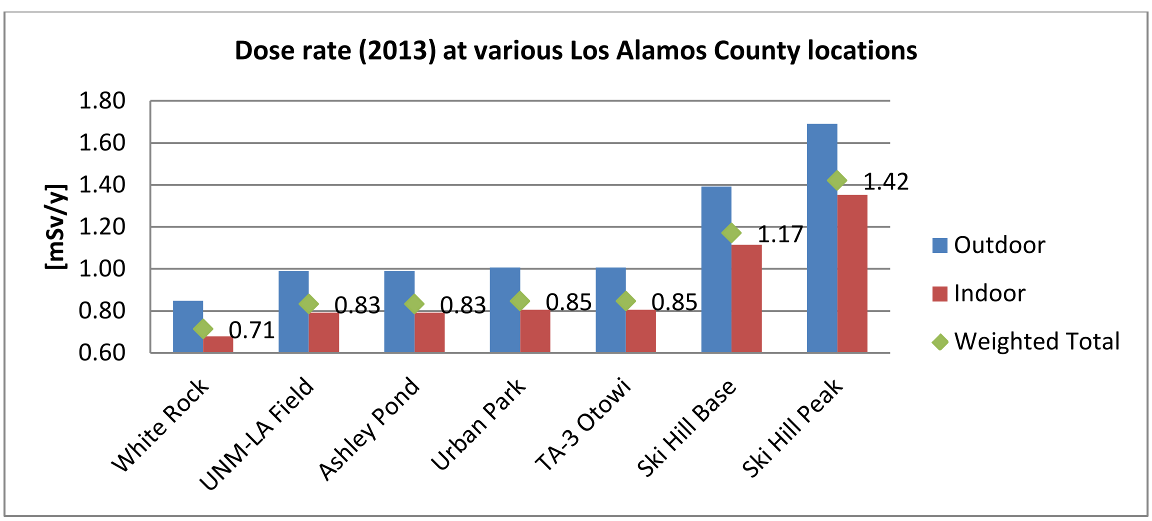

Figure 7: Cosmic ray dose rate from CARI-6 calculations at the elevations of several locations in Los Alamos County incorporating a housing factor of 0.8 and 80% time spent indoors. (Federal Aviation Administration, 2012)

The results returned by CARI-6 clearly showed the effect of the solar cycle on cosmic ray dose rates. Therefore, a final value for cosmic ray dose rate using the CARI-6 method would be averaged over the solar cycle and weighted using a housing factor of 0.8. Correction for solar activity required averaging the data over 11 years, from 2002-2013. Figure 8 and Figure 9 depict this effect. At 2225 m, weighted cosmic effective dose rate in Los Alamos was 0.84 $\frac{\mathrm{mSv}}{\mathrm{y}}$.

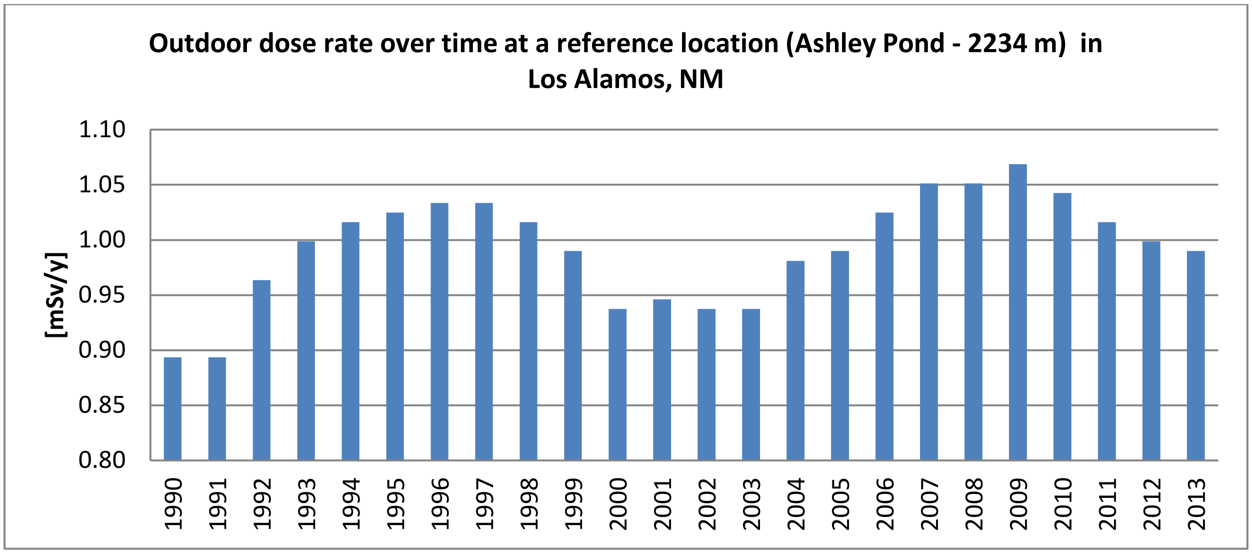

Figure 8: Cosmic ray dose rate variation over time at a reference location (Ashley Pond) in Los Alamos (Federal Aviation Administration, 2012)

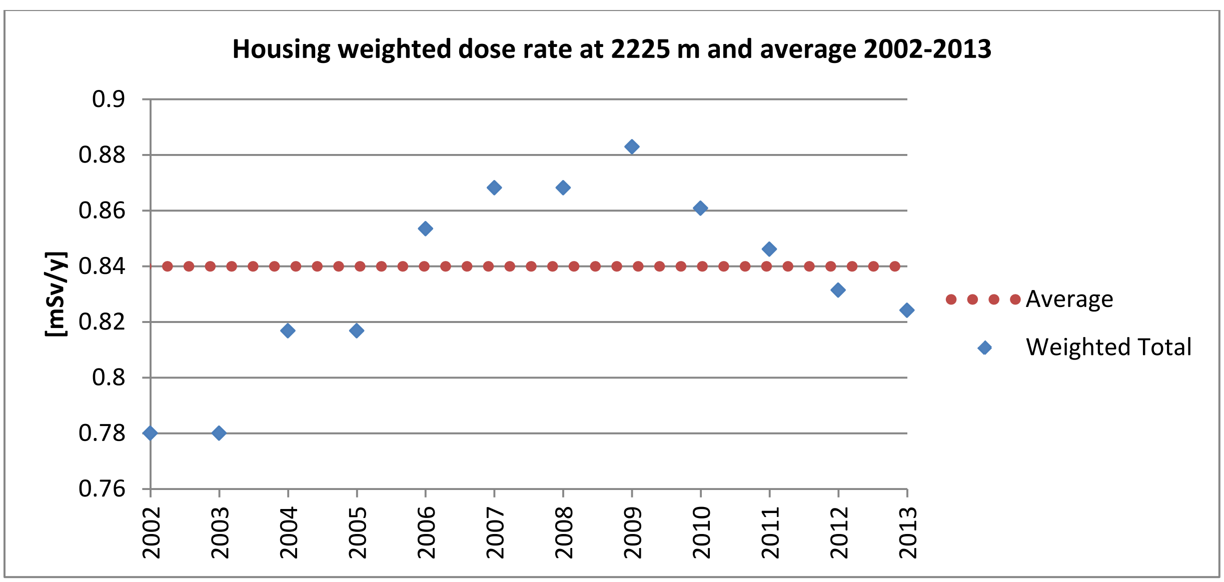

Figure 9: Temporal variation of the cosmic ray dose based on solar activity and average of 11 year cycle (Federal Aviation Administration, 2012). A housing factor of 0.8 and 80% time spent indoors are applied.

Terrestrial Radiation Dose

External

The concentrations of primordial radionuclides in soil are generally within ranges found in the United States and world, but appear to be above national and world averages/medians. However, the soil concentration of ^{40}K found by Ryti et al (1998) is much higher than the listed United States (UNSCEAR, 2000) range but falls within the ranges listed for areas around the world and is consistent with the USGS data shown in Appendix 1. Both mean concentrations and upper tolerance limit concentrations (estimating the upper bound of the background distribution) are provided. Table 1 compares soil levels of these radionuclides and the doses received using the accepted dose rate calculations (Equation 2 and Equation 3). The conservative estimated external terrestrial dose rate to Los Alamos County residents is 0.91 $\frac{\mathrm{mSv}}{\mathrm{y}}$.

Table 1: Mean and upper tolerance limit (UTL) soil concentrations of regional soil (Ryti, Longmire, Broxton, Reneau, & McDonald, 1998, pp. 45 Table 6.0-2) with comparisons to United States and worldwide concentration medians (UNSCEAR, 2000, p. 115 Table 5). Annual effective doses are estimated for the given soil concentrations.

Radionuclide	Los Alamos County $\left[\frac{\mathrm{Bq}}{\mathrm{kg}}\right]$		United States $\left[\frac{\mathrm{Bq}}{\mathrm{kg}}\right]$		World $\left[\frac{\mathrm{Bq}}{\mathrm{kg}}\right]$	
	Soil Mean	Soil UTL	Mean	Range	Median of Means	Median Range
^{40}K	1104	1362	370	100-700	400	140-850
^{232}Th	53	86	35	4-130	30	11-64
^{238}U	45	85	35	4-140	35	16-110
$\dot{D}_{\mathrm{air}} \left[\frac{\mathrm{nGy}}{\mathrm{h}}\right]$	99	148	53	-	51	-
Annual effective dose rate $\left[\frac{\mathrm{mSv}}{\mathrm{y}}\right]$	0.61	0.91	0.32	-	0.31	-

Compiled DPRNET measurements of external radiation dose (including cosmic) found a mean of $1.24 \pm 0.03 \frac{\mathrm{mSv}}{\mathrm{y}}$ (95% confidence level), with a range from 0.99 to 1.54 $\frac{\mathrm{mSv}}{\mathrm{y}}$. These data were based on site specific averages over the duration of use of individual monitoring locations, and were selected as being the most representative of background external dose rates at LANL. Increasing dose rates were observed to be due to increased elevation and increased natural concentrations of terrestrial radiation sources. The two highest data points are located in canyons, indicating that the detectors were irradiated by gamma emitters in the soil from both the canyon floor and the walls. Lower values are due to lower elevations as well as areas where the terrestrial radiation is shielded, perhaps for areas which are covered with asphalt.

NEWNET measurements of external radiation dose (including cosmic) are available online, and can be manipulated and compiled as in Figure 10. For example, from February 2013 to February 2014, external dose rates at Los Alamos High School averaged 1.2 $\frac{\mathrm{mGy}}{\mathrm{y}}$ (1.2 $\frac{\mathrm{mSv}}{\mathrm{y}}$ deep dose equivalent) with a range from 1.1 to 1.8 $\frac{\mathrm{mGy}}{\mathrm{y}}$ (recorded as an average of 14.3 $\frac{\mu\mathrm{R}}{\mathrm{h}}$ ranging from 13.0 to 21.6 $\frac{\mu\mathrm{R}}{\mathrm{h}}$). Spikes in the exposure rate are due to increased surface radon concentrations during precipitation events.

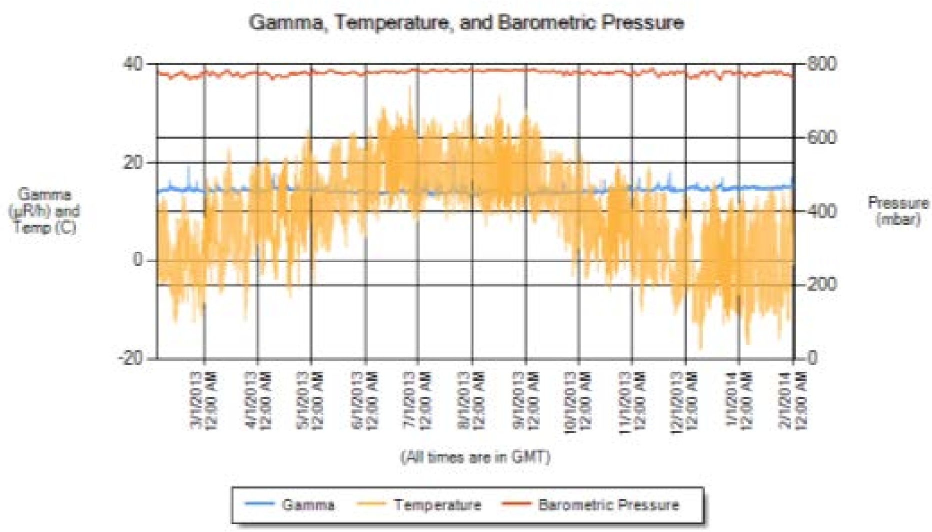

Figure 10: NEWNET data from Los Alamos High School from February 2013 through February 2014 showing temperature diurnal and annual fluctuation (orange) [^{o}C], pressure (red) [mbar], and gamma exposure (blue)$\left[\frac{\mu\mathrm{R}}{\mathrm{h}}\right]$

NEWNET data from 2002-2013 resulted in the average values for each station plotted in Figure 11 and an overall average of 1.35 $\frac{\mathrm{mGy}}{\mathrm{y}}$ (range from 0.97 to 1.60 $\frac{\mathrm{mGy}}{\mathrm{y}}$), which converts to 1.35 $\frac{\mathrm{mSv}}{\mathrm{y}}$ deep dose equivalent. The ten year average value would account for any variation due to the solar cycle, although this variation has not been seen. NEWNET is not sensitive to neutrons.

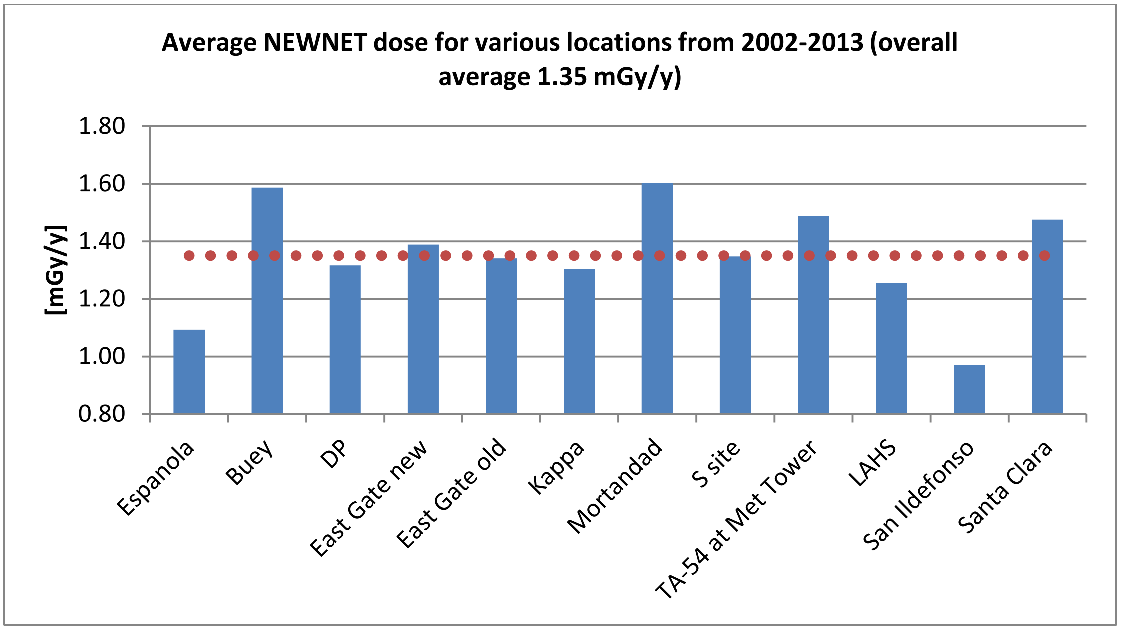

Figure 11: Radiation dose recorded by NEWNET for 2002-2013 at various locations (includes cosmic dose without neutrons)

The aerial radiological survey in 2011 and 2012 compiled a variety of external count rate maps. Figure 12 is a summary map of the flyover data, and Appendix II provides information on the variation in natural nuclide concentrations over the town site. The range of external terrestrial dose rates was from 0.43 to 1.7 $\frac{\text{mSv}}{\text{y}}$ (5.1 to 19.9 $\frac{\mu\text{R}}{\text{h}}$ with an exposure to tissue dose conversion of 9.6 $\frac{\text{mSv}}{\text{R}}$) for the area around the Los Alamos town site, with (DOE, 2012). The highest values on the map are in areas of LANL which are not accessible to the public.

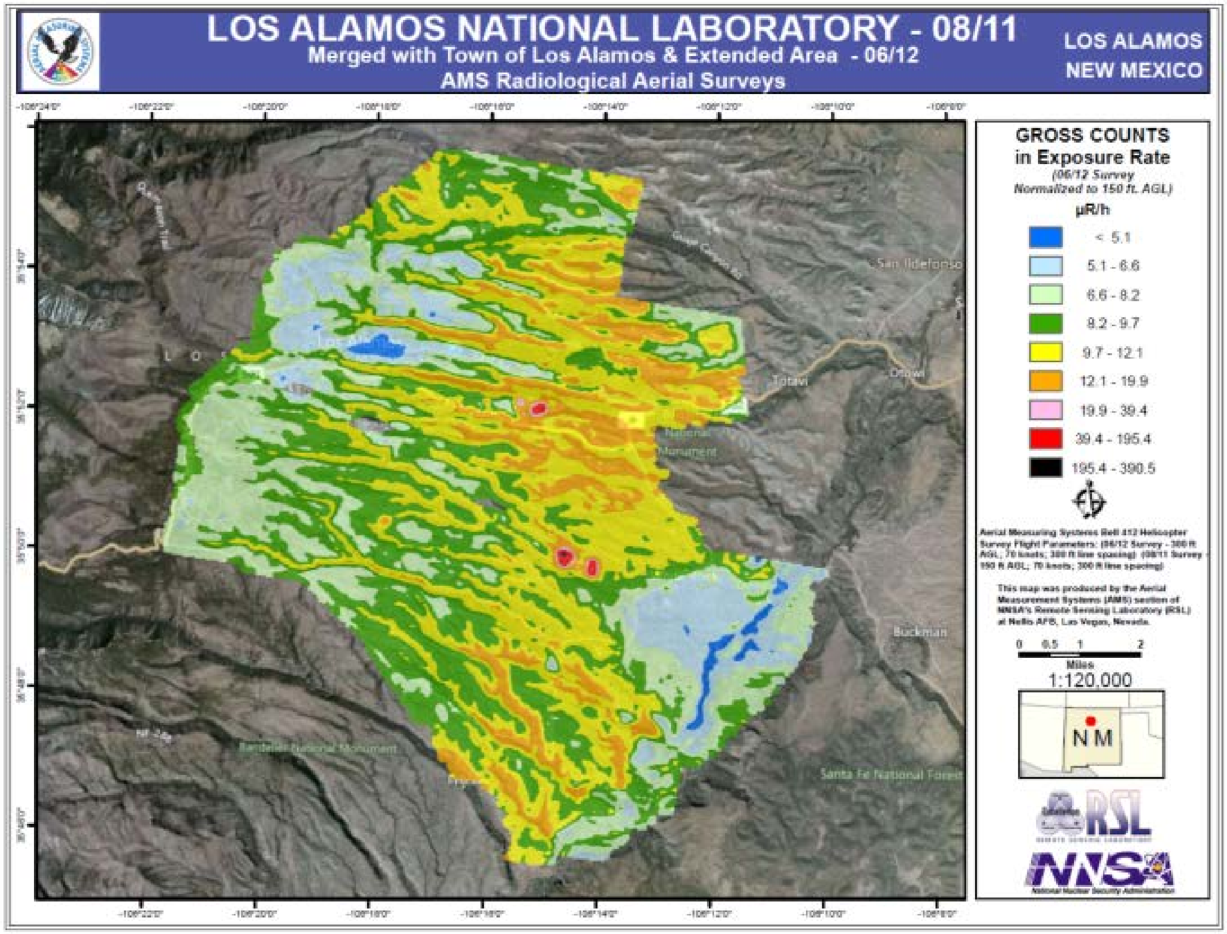

Figure 12: Terrestrial exposure rate for Los Alamos town site and LANL derived at a height of 1 m

Radon (Internal Inhalation) Dose

Radon, one of the largest contributors to a person's background radiation dose, has been measured in Los Alamos County at concentrations which appear to be on the upper end of the continuum. A 2009 study by Whicker and McNaughton found an average concentration in homes of 75 $\frac{\mathrm{Bq}}{\mathrm{m}^3}$ (median of 55.5 $\frac{\mathrm{Bq}}{\mathrm{m}^3}$ and range from 22.2 to 233.1 $\frac{\mathrm{Bq}}{\mathrm{m}^3}$). In office spaces at Los Alamos National Laboratory, this paper found a mean of 24.3 $\frac{\mathrm{Bq}}{\mathrm{m}^3}$, a median of 18.5 $\frac{\mathrm{Bq}}{\mathrm{m}^3}$, and a range from 11.1 to 107.3 $\frac{\mathrm{Bq}}{\mathrm{m}^3}$. Their data are represented in the box and whisker plot in Figure 13. For comparison, the U.S. EPA recommends an action level of 148 $\frac{\mathrm{Bq}}{\mathrm{m}^3}$ for Rn, while OSHA recommends 1200 $\frac{\mathrm{Bq}}{\mathrm{m}^3}$ for office spaces.

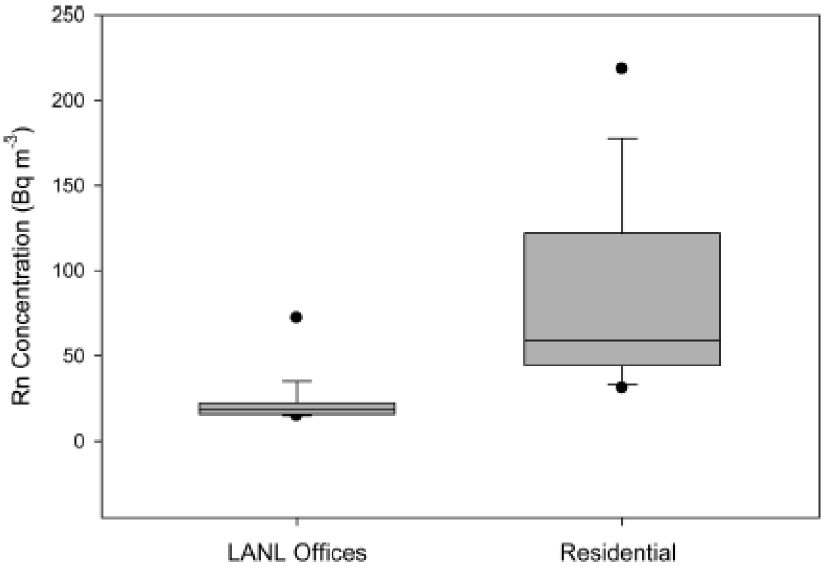

Figure 13: Box and whisker plot of radon concentrations in LANL office and work spaces where boxes represent 25%-75% of the values and whiskers represent 95%. Outliers are represented by dots outside the 95% range, and the central lines reflect the medians

For an individual working 2,000 h/y and spending 5,746 h/y at home, the total dose averaged 2.6 $\frac{\text{mSv}}{\text{y}}$ (median 1.9 $\frac{\text{mSv}}{\text{y}}$). Full-time office workers received on average about eight times more exposure at home (2.3 $\frac{\text{mSv}}{\text{y}}$) than at work (0.3 $\frac{\text{mSv}}{\text{y}}$). Alternatively, for an individual spending 85% of his or her time at home (7,446 h/y), the average dose was 3.0 $\frac{\text{mSv}}{\text{y}}$ (median 2.2 $\frac{\text{mSv}}{\text{y}}$) (Whicker & McNaughton, 2009). For comparison, the U.S. EPA action level for homes is said to correspond to a dose of 4 $\frac{\text{mSv}}{\text{y}}$, while the OSHA recommendation is said to correspond to a dose of 8 $\frac{\text{mSv}}{\text{y}}$.

Food & Water (Internal Ingestion) Dose

This report defaults to the NCRP 160 summed value for internal ingestion sources of 0.29 $\frac{\text{mSv}}{\text{y}}$, or 0.28 $\frac{\text{mSv}}{\text{y}}$ not including the 0.01 $\frac{\text{mSv}}{\text{y}}$ associated with cosmogenic nuclides (NCRP, 2009, p. 12). This decision requires the assumption that drinking water is not significantly different from national averages in levels of radionuclides, and that foods consumed by most residents in Los Alamos are similar to those consumed by the US population as a whole. The first assumption is valid because levels of radionuclides in water have not been reported by the Department of

Public Utilities to be above average. The second is valid because a diet consisting primarily of foods bought at a local grocery store would be composed of imported foods which are produced and packaged offsite and sold around the country. Los Alamos County has no commercial produce or ranch stock. The only significant locally grown food would be from home gardens and fruit trees. Annual site environmental reports have repeatedly found that that eating wild meats and native plants and produce from the area (e.g., deer, elk, fish) do not contribute to doses beyond that expected from wild foods anywhere else in the US.

Water data is based on Los Alamos County drinking water quality reports, as shown in Table 2. The total dose from ingestion of water is estimated at 6 $\frac{\mu\mathrm{Sv}}{\mathrm{y}}$. For comparison, the NCRP 160 estimated range was 11 to 67 $\frac{\mu\mathrm{Sv}}{\mathrm{y}}$ (Appendix B Table B1). Although the Los Alamos aquifer is very clean (low uranium content) compared to other water sources, the divergence from the NCRP 160 range might be due to a biased focus on positive reported results in the published values.

Table 2: Drinking water radionuclide concentrations (measured as gross alpha / gross beta) and corresponding doses

Year	Measurement	Concentration	Conversion	Dose [µSv]
2013	Gross alpha	0.944 pCi/L	$\frac{4\ \mathrm{mrem}}{15\ \mathrm{pCi/L}} \times 10\,\frac{\mu\mathrm{Sv}}{\mathrm{mrem}}$	2.5
2008	Gross alpha	0.18 pCi/L	$\frac{4\ \mathrm{mrem}}{15\ \mathrm{pCi/L}} \times 10\,\frac{\mu\mathrm{Sv}}{\mathrm{mrem}}$	0.48 (mostly U)
2007	Gross alpha	3.44 pCi/L	$\frac{4\ \mathrm{mrem}}{15\ \mathrm{pCi/L}} \times 10\,\frac{\mu\mathrm{Sv}}{\mathrm{mrem}}$	9.2
2013	Gross beta/gamma	1.29 pCi/L	$\frac{4\ \mathrm{mrem}}{50\ \mathrm{pCi/L}} \times 10\,\frac{\mu\mathrm{Sv}}{\mathrm{mrem}}$	1.0
2008	Gross beta/gamma	2.65 pCi/L	$\frac{4\ \mathrm{mrem}}{50\ \mathrm{pCi/L}} \times 10\,\frac{\mu\mathrm{Sv}}{\mathrm{mrem}}$	2.1
2007	Gross beta/gamma	4.0 pCi/L	$\frac{4\ \mathrm{mrem}}{50\ \mathrm{pCi/L}} \times 10\,\frac{\mu\mathrm{Sv}}{\mathrm{mrem}}$	3.2
Average dose from gross alpha (2013, 2008, 2007)				4.1
Average dose from gross beta/gamma (2013, 2008, 2007)				2.1
Total water dose (average)				6.2

Anthropogenic Radiation Dose

Medical

Due to large uncertainties and difficulties obtaining information about community specific procedure rates, the NCRP 160 value of 3.0 mSv/y average has been retained. However, some investigation has been conducted to investigate this term. Medical doses can be estimated more accurately for a community when information is provided about population demographics. Table 3 describes the population of Los Alamos by age. Los Alamos County has an equivalent fraction of its population under 18 years old, a slightly smaller fraction between the ages of 18-65, and a slightly larger population older than 65 years compared with the United States overall. Because populations of older individuals are more likely to receive radiological diagnostic exams and treatments, it is possible that the NCRP 160 value is an underestimate of the average dose to residents of Los Alamos County. On the other hand, data have shown that procedure rates for New Mexico are lower than national averages (Hawkley & Whicker), which would tend to reduce the average dose for medical procedures.

Table 3: 2013 data on age distributions for residents in Los Alamos County, the State of New Mexico, and the U.S. population (U.S. Department of Commerce, 2014)

	Los Alamos	New Mexico	U.S.A
Population	17,798	2,085,287	316,128,839
% <18 years	23.3	24.3	23.3
% 18-65 years	60.2	61.0	62.3
% ≥ 65 years	16.5	14.7	14.1

Fallout

While levels vary by region and can also vary locally, the concentrations in Table 4 can be attributed to fallout around Los Alamos. RESRAD runs show about 0.026 $\frac{\mathrm{mSv}}{\mathrm{y}}$ from fallout due to radionuclides at these concentrations, with the majority of the dose being due to ^{137}Cs and ^{90}Sr. Appendix III provides more detail on the input parameters and outputs.

Table 4: Average concentrations of fallout nuclides of interest in regional soils (Ryti, Longmire, Broxton, Reneau, & McDonald, 1998, pp. 18 Table 3.3-2)

Nuclide	Concentration $\left[\frac{\text{pCi}}{\text{g}}\right]$	Concentration $\left[\frac{\text{Bq}}{\text{kg}}\right]$
^{241}Am	0.0064	0.24
^{238}Pu	0.0054	0.20
^{239}Pu	0.015	0.56
^{137}Cs	0.42	16
^{90}Sr	0.36	13
^{3}H	$0.185\,\frac{\text{pCi}}{\text{mL}} \times \frac{12\%\text{ soil moisture}}{88\%\text{ soil dry mass}} = 25\,\frac{\text{pCi}}{\text{g}}$	0.93

Consumer Products (Adjusted Cigarette Dose)

Inhalation of cigarette smoke can be a significant contributor to radiation dose. Of the NCRP 160 consumer products value of $0.13\,\frac{\text{mSv}}{\text{y}}$, 35% of the collective effective dose ($0.05\,\frac{\text{mSv}}{\text{y}}$) was due to cigarette smoking ($0.08\,\frac{\text{mSv}}{\text{y}}$ was due to other sources).

A 2011 report indicated that 20.1% of New Mexicans smoke compared to 19.8% of the population of the United States. For Los Alamos County specifically, only 6.7% of adults smoke, while 17.7% of youth (ages 14-18) smoke (LACHC, 2011). Radionuclides in smoke contribute to dose according to the estimation from NCRP 160 that $1\,\frac{\text{cigarette}}{\text{day}} = 18\,\frac{\mu\text{Sv}}{\text{year}}$. This report also stated that the mean number of cigarettes smoked per day in 2004 was 17 (NCRP, 2009, p. 156).

Therefore, if there are $2{,}085{,}287 \times 0.2 = 417{,}057$ smokers in NM, and on average they each smoke 17 cigarettes per day:

$$417{,}057\text{ smokers} \times 18 \times 10^{-6}\,\frac{\left[\frac{\text{Sv}}{\text{y}}\right]}{\left[\frac{\text{cigarette}}{\text{d}}\right]} \times 17\,\frac{\text{cigarette}}{\text{d}} = 127\text{ smoker}\cdot\text{Sv}$$

This would be, on average $\frac{127}{2085287} = 0.06\,\frac{\text{mSv}}{\text{y}}$ for a member of the NM population. This calculation would bring the total consumer product dose up to $0.14\,\frac{\text{mSv}}{\text{y}}$.

Alternatively, if $100\% - 23.3\% = 76.7\%$ of the population of Los Alamos County is composed of adults, then $17{,}798 \times 0.767 \times 0.067 = 915$ adults are smokers. If 17.7% of youth ages 14-18 (4/19 of all youth ages 0-18) smoke, then $17{,}798 \times 0.233 \times \frac{4}{19} \times 0.177 = 154\ \text{youth}$ are smokers. The dose could be estimated as:

$$(915 + 154)\ \text{smokers} \times 18 \times 10^{-6} \frac{\left[\frac{\text{Sv}}{\text{y}}\right]}{\left[\frac{\text{cigarette}}{\text{d}}\right]} \times 17 \frac{\text{cigarette}}{\text{d}} = 0.327\ \text{smoker} \cdot \text{Sv}$$

This would be, on average $\frac{0.327}{17{,}798} = 0.02 \frac{\text{mSv}}{\text{y}}$ for a resident of the Los Alamos County. This calculation would result in a total consumer product dose of $0.10 \frac{\text{mSv}}{\text{y}}$.

Discussion and Conclusions

Currently, an estimation of the background dose to residents of Los Alamos County is conducted and presented in the Annual Site Environmental Report using the doses listed in Table 5.

Table 5: Contributions to Los Alamos background dose as used in current environmental reports

$\frac{mSv}{y}$	Source	Reference
0.7 (0.5-0.9)	Cosmic	(Bouville & Lowder, 1988)
1 (0.5-1.5)	Terrestrial external	(DOE, 2012)
2.7	Rn and progeny	(Whicker & McNaughton, 2009)
0.3	Primordial internal	(NCRP, 2009)
3	Medical/dental	(NCRP, 2009)
0.1	Man-made	(NCRP, 2009)
7.8	Total	

Existing as well as new dose values have been investigated in this report, and the rationales behind them are summarized in Table 6 and Table 7.

Table 6: Summary of annual effective doses from natural sources estimated in this report

Source	Value$\left[\frac{mSv}{y}\right]$	Reference/rationale
Cosmic	0.6 0.8 (with neutrons) 0.63 0.84 (with neutrons) 0.66 0.88 (with neutrons)	Bouville & Lowder equation 2225 m Bouville & Lowder value extrapolated for neutrons CARI-6 value minus 25% neutrons CARI-6 housing factor weighted, 11 year averaged, 2225 m Reuter & Stokes equation 2225 m Reuter & Stokes value extrapolated for neutrons
Cosmic neutrons	0.21 0.2 0.19	25% of CARI-6 value Additional 25% added to Bouville & Lowder value Estimate at 2225 m from linear extrapolation
Cosmogenic	0.01	NCRP 160 value associated primarily with ^{14}C, ^{87}Rb
External (including cosmic)	1.24 1.2 deep dose eq. 1.35 deep dose eq.	DPRNET NEWNET Feb 2013 – Feb 2014 (no neutrons) NEWNET average 2002-2013 (no neutrons)
External (terrestrial only)	0.61 0.91 0.43-1.7 0.4 0.72	Estimation using accepted equation and Ryti et al mean conc. Estimation using accepted equation and Ryti et al UTL conc. Aerial radiological survey DPRNET minus CARI-6 cosmic value NEWNET avg 2002-2013 minus CARI-6 cosmic (no neutrons)
Internal inhalation (radon & progeny)	2.6 3.0	Whicker & McNaughton average for a working individual Whicker & McNaughton average for a homebound individual
Internal ingestion	0.28	NCRP 160: Los Alamos population likely resembles US

		population in consumption of food and water containing radionuclides – difficult to evaluate – US average has been retained (subtracted 0.01 cosmogenic which is included in NCRP 160 sum)

Table 7: Doses from anthropogenic sources estimated in this report

Source	Value $\left[\frac{\text{mSv}}{\text{y}}\right]$	Reference/rationale
Medical	3.00	NCRP 160 but Los Alamos population may differ from national average in age range and number of procedures/dose per capita – difficult to evaluate – US average has been retained
Fallout	0.26	RESRAD run using Ryti et al concentrations
Consumer products	0.10	NCRP 160 dose with 35% adjusted for LA County smoking rate
Industrial & other	0.003	NCRP 160

Decisions for Los Alamos Effective Doses

The predominant impacts of living in the LA county environment are from increased altitude (increased cosmic) and increased natural radionuclide concentrations (increased terrestrial external and inhalation). Deviations from the national dose averages are greatest in these categories. Table 8 summarizes the E_{LA} and E_{US} values and calculates a summed average radiation dose for comparison to NCRP 160.

Table 8: Summed contributions to background dose for residents of Los Alamos County and US national averages

Source	E_{LA} $\left[\frac{\text{mSv}}{\text{y}}\right]$	Reference	E_{US} $\left[\frac{\text{mSv}}{\text{y}}\right]$	NCRP 160
Cosmic	0.84	CARI-6	0.33	Population-weighted average annual effective dose corrected for shielding and time spent indoors & averaged over 11 year solar cycle p.31
Cosmogenic	0.01	NCRP 160, UNSCEAR 2000	-	Included as a component of internal/ingestion, primarily from ^{14}C, ^{87}Rb
Terrestrial External	0.91	Ryti et al, UNSCEAR 2000	0.21	0.21 population-weighted annual effective dose p. 42
Internal Inhalation (Radon and progeny)	3.0	Whicker & McNaughton 2009	2.28	Average annual effective dose for: ^{222}Rn (0.05) and progeny (2.07) p. 62, using a nominal central estimate of 40% equilibrium factor p. 51, 10 $\frac{\text{mSv}}{\text{WLM}}$ dose conversion coefficient p.59, as well as ^{220}Rn and progeny (0.16) using 3.3 $\frac{\text{mSv}}{\text{WLM}}$ p. 62
Internal Ingestion	0.28	NCRP 160 minus 0.01 contribution from cosmogenic	0.29	Arithmetic mean summing contributions from ^{40}K (0.15), ^{232}Th and ^{238}U series (0.13) and other/cosmogenic (0.01) Table 3.14 p. 75
Medical	3.00	NCRP 160	3.00	Components include 0.33 from conventional radiography, 0.43 from interventional fluoroscopy, 1.47 from computed tomography (CT), and 0.77

				from nuclear medicine. External beam radiation therapy (1.2) was not included due to small affected population
Fallout	0.026	RESRAD run using Ryti et al	-	(not included) < 0.01 from UNSCEAR 2000
Consumer products	0.10	NCRP 160, LACHC 2011	0.13	Contributions from cigarette smoking 35%, building materials 27%, commercial air travel 26%, and lesser fractions from mining/agriculture, combustion of fossil fuels, highway and road construction materials, glass and ceramics, and other sources
Industrial & Other Anthropogenic	0.003	NCRP 160	0.003	industrial, security, medical, educational, research
Total	8.2	(rounded value)	6.2	(rounded value)

Natural Variation & Uncertainties

The variation in individual exposures is driven by a combination of factors, and individual variation from the average doses can be quite large. Therefore, while a study such as this can help make relative comparisons of regional effective doses to nationwide background dose estimates, the value of E_{LA} is not intended to accurately describe the actual dose to specific individuals in Los Alamos County. Table 9 provides a list of some of the major uncertainties associated with each dose source.

Some general considerations can be made. Background dose rates are generally smaller inside of buildings as opposed to outside, and generally smaller on top of mesas than in canyons. The primary factors that can cause a subgroup to vary from the population averages include history of past radiological medical procedures and radon exposures (UNSCEAR 2000). Therefore, knowledge of these details at minimum would be necessary to adjust E_{LA} for any specific community member.

Table 9: Uncertainty contributions for various dose sources

Dose Source	Potential Associated Uncertainties
Cosmic	Elevation Time spent outdoors vs. indoors Composition of buildings
Cosmogenic	Small dose and almost no variation because the atmosphere is well mixed
Terrestrial External	Soil concentration Irradiation geometry Shielding associated with pavement/buildings Time spent outdoors vs. indoors

Internal Inhalation (Radon)	Dose conversion coefficient – assumptions about aerosol and properties of respiratory tract (NCRP, 2009, p. 56), find a GSD of 1.6 mSv/WLM to be consistent between various models/assumptions/opinions (NCRP, 2009, p. 59) Rn equilibrium concentration – nominal indoor estimate of 40% with an uncertainty range of 30-50% (NCRP, 2009, p. 51), outdoor estimate can vary, average of 60% (NCRP, 2009, p. 55) Time spent at each measured location
Internal Ingestion	Source of food items and water
Medical	Number of procedures experienced
Fallout	Small dose; variation to first order depends on precipitation amount
Consumer	Smoking habits Frequency/duration of aircraft travel Use/consumption of other products
Industrial & Other Anthropogenic	Living/working near significant radiation sources
LANL Impact	Proximity to Laboratory and contaminated zones
LANL Occupational	Frequency/duration of work with radioactive materials

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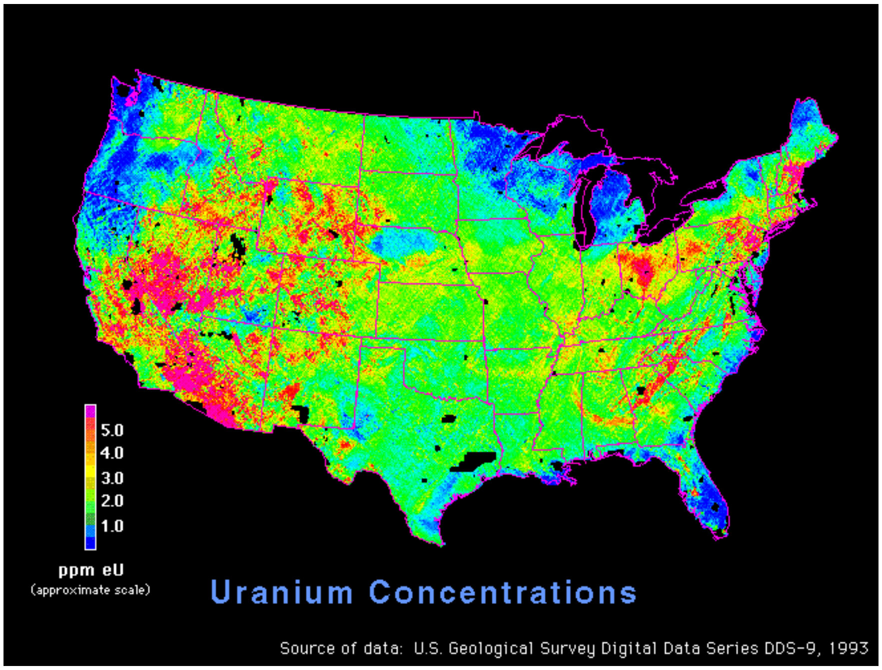
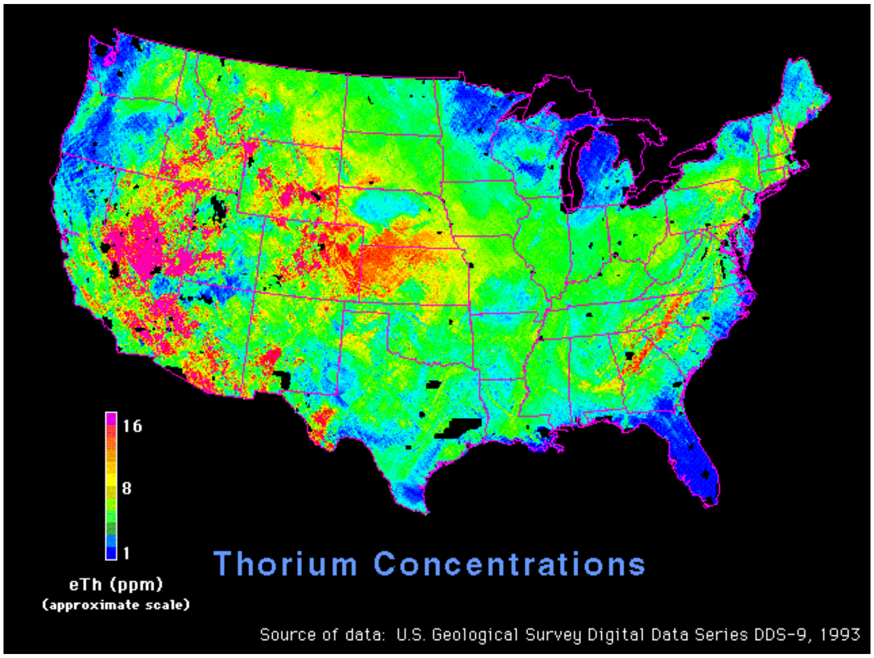
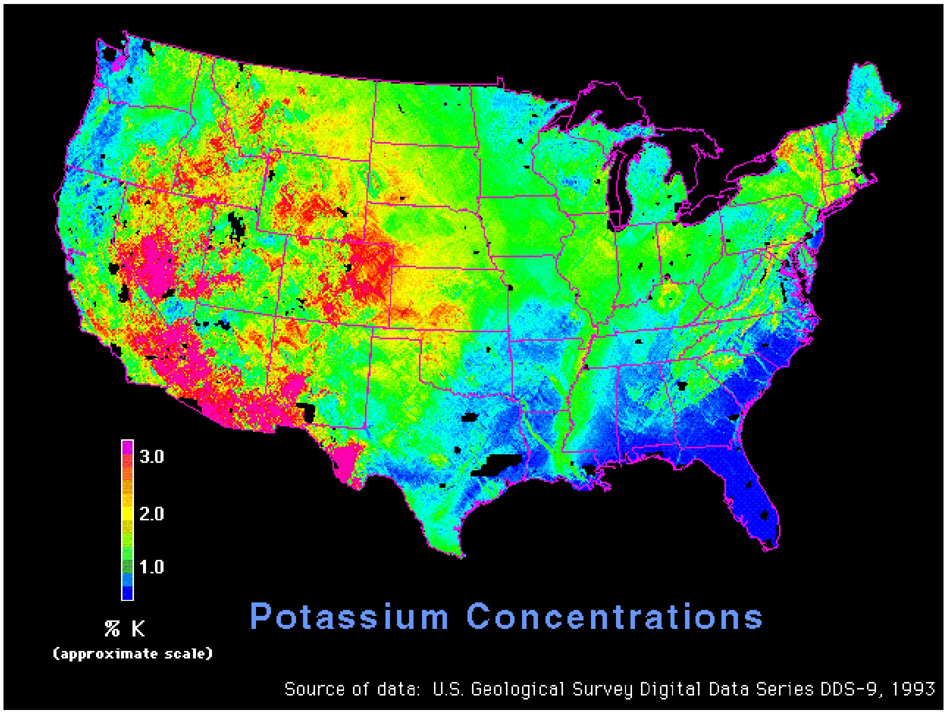
Appendix I

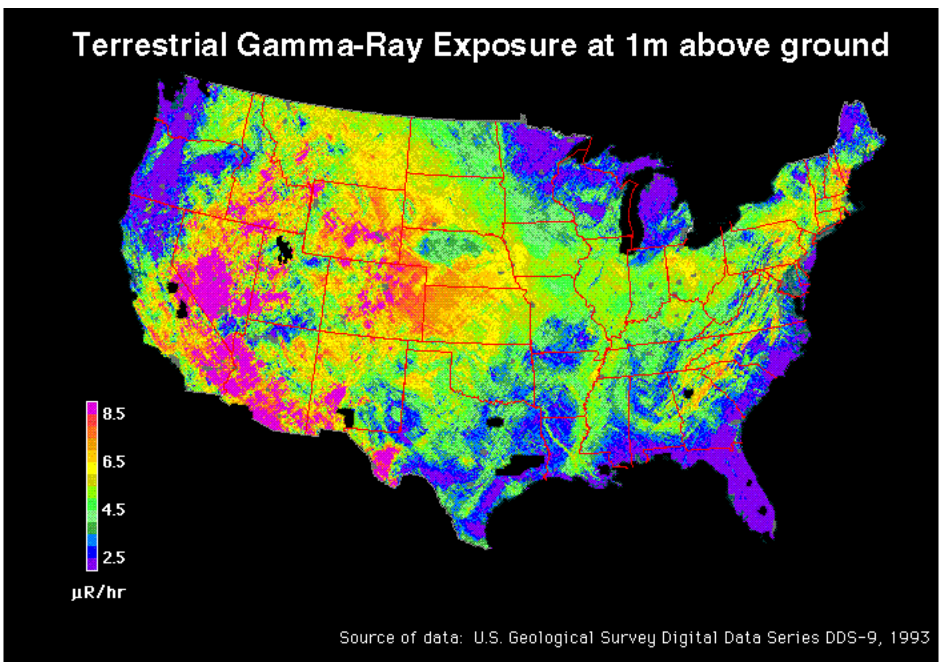
USGS Soil Concentration Data

Data from the United States Geological Survey on levels of primordial radionuclides contributing to terrestrial gamma ray exposure (USGS, 1993).



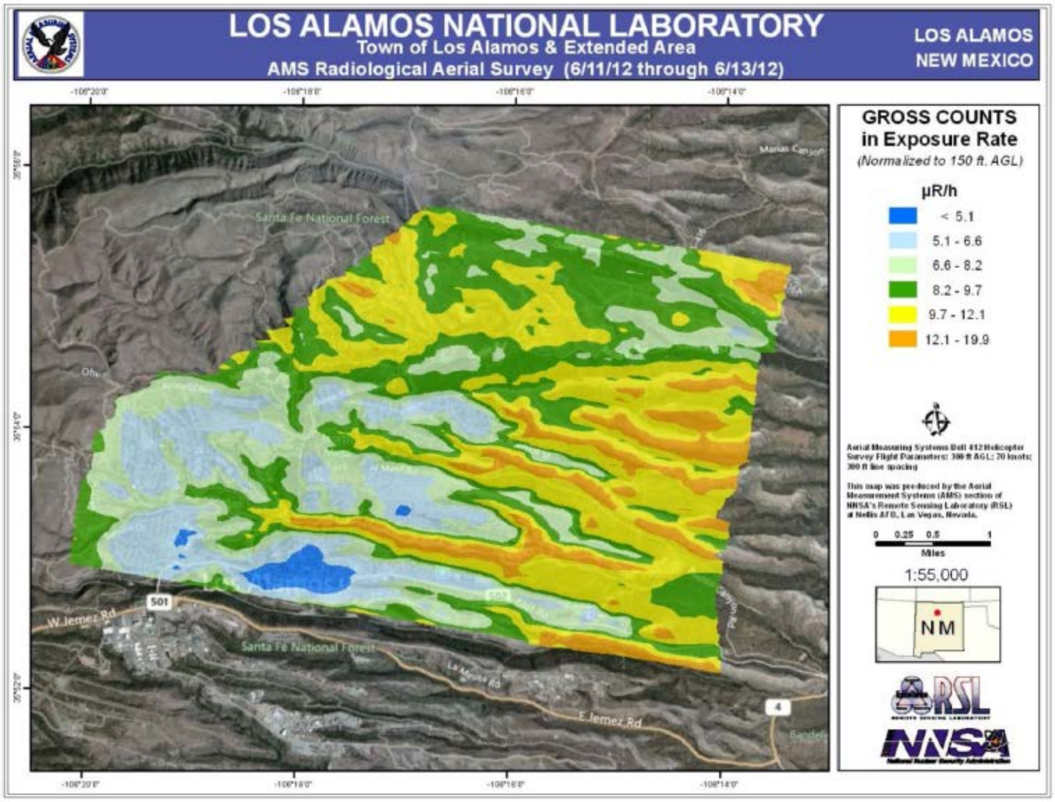


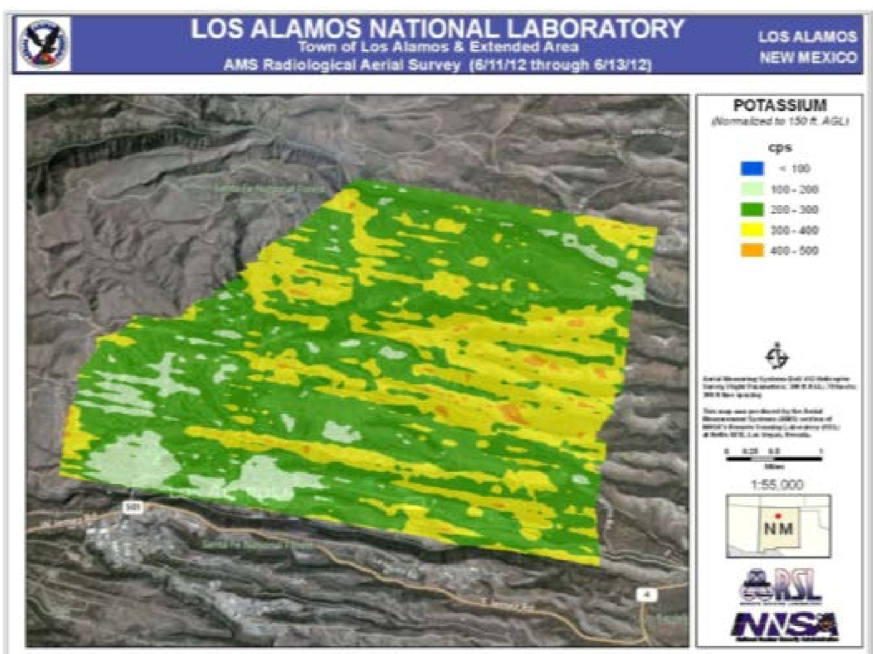

3.0
2.0
1.0
% K
(approximate scale)
Potassium Concentrations
Source of data: U.S. Geological Survey Digital Data Series DDS-9, 1993

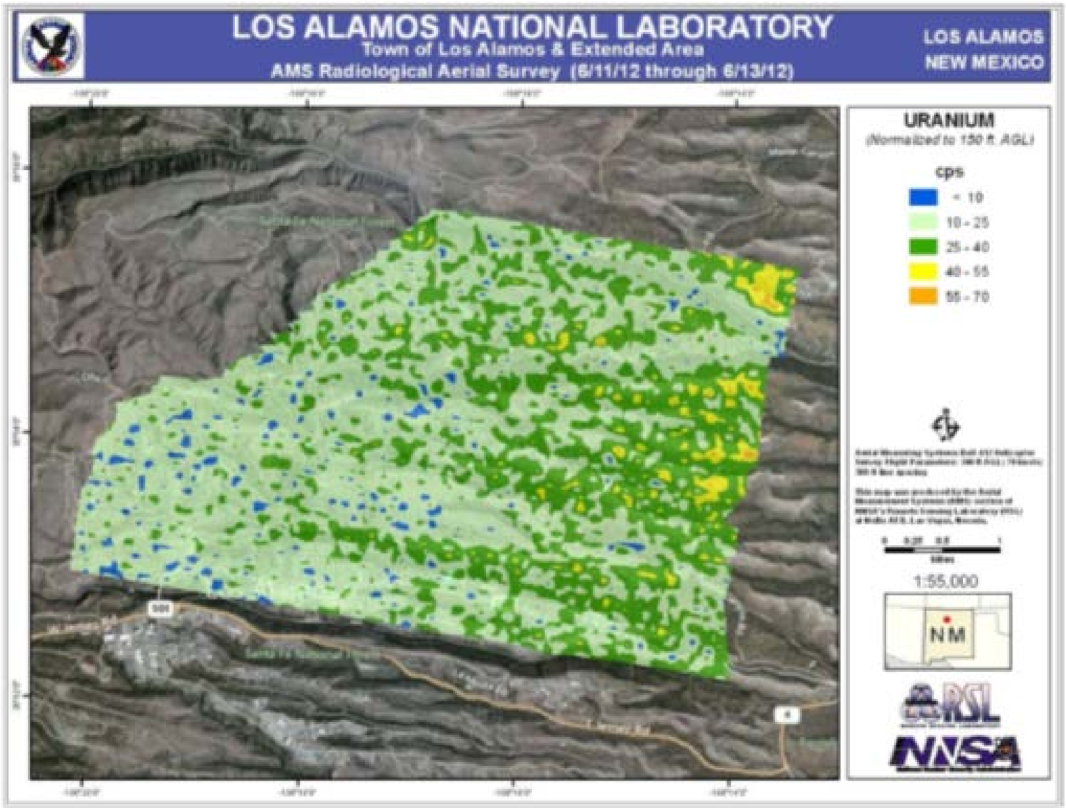

Terrestrial Gamma-Ray Exposure at 1m above ground
8.5
6.5
4.5
2.5
µR/hr
Source of data: U.S. Geological Survey Digital Data Series DDS-9, 1993

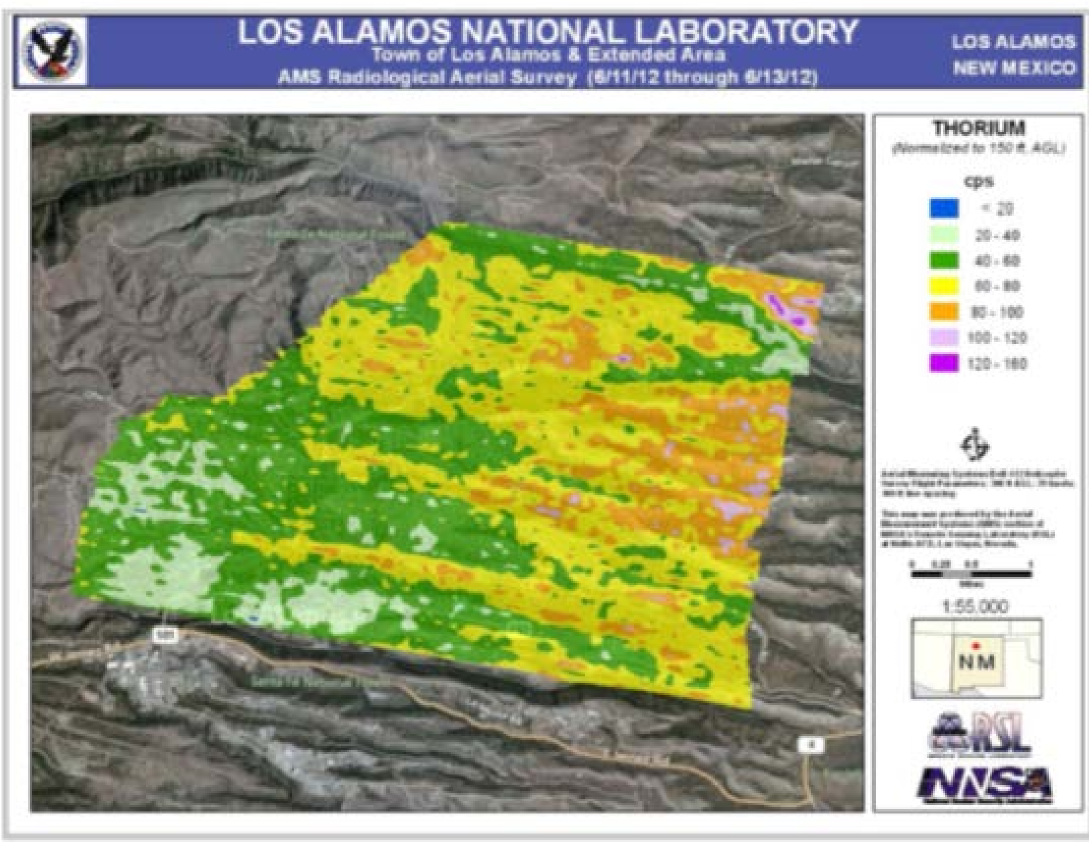
Appendix II

Aerial Survey of Los Alamos Townsite






LOS ALAMOS NATIONAL LABORATORY
Town of Los Alamos & Extended Area
AMS Radiological Aerial Survey (6/11/12 through 6/13/12)
LOS ALAMOS
NEW MEXICO
URANIUM
(Normalized to 150 ft. AGL)
cps
< 10
10 - 25
25 - 40
40 - 55
55 - 70
1:55,000
NM
RSL
NNSA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Town of Los Alamos & Extended Area
AMS Radiological Aerial Survey (6/11/12 through 6/13/12)
LOS ALAMOS
NEW MEXICO
THORIUM
(Normalized to 150 ft. AGL)
cps
< 20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 120
120 - 160
1:55,000
NM
RSL
NNSA

Appendix III

RESRAD Inputs for Fallout Dose

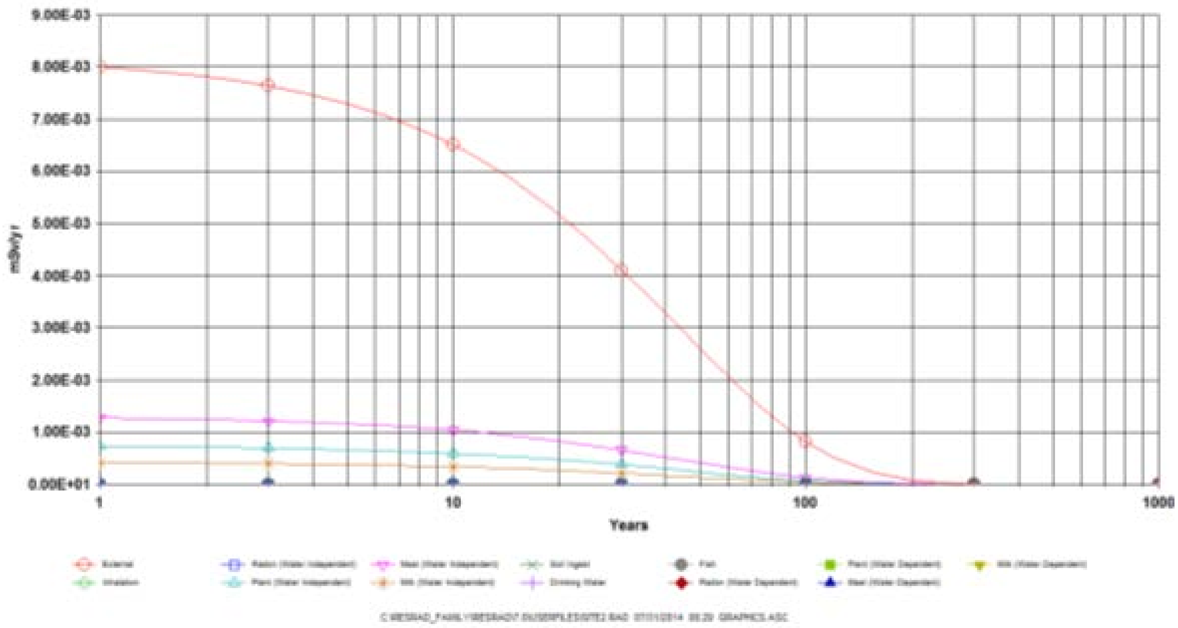
Nuclide	Activity Conc.		T_R	Decay	Exposure Pathway
	[pCi/g]	[Bq/kg]	y		
Pu-239	0.015	0.56	24,000 y	α 5155 keV (0.733) 5143 keV (0.151) 5105 keV (0.115)	Resuspension onto plant material and inhalation
Pu-238	0.0054	0.20	87.7 y	α 4661 keV (0.23) 4470 keV (0.20) 4430 keV (0.11)	Resuspension onto plant material and inhalation
Cs-137	0.42	16	30.17 y	β^- 512 keV (0.946) (Ba-137m 2.6 min) γ 662 keV (0.8998)	External exposure Soft tissue (like K) when incorporated (meat/plants/milk)
H-3	$0.185\,\frac{\text{pCi}}{\text{L}} \times \frac{12}{88} = 0.025\,\frac{\text{pCi}}{\text{g}}$	0.93	12.3 y	β^- 18.6 keV (1)	Whole body internal even dist.
Am-241	0.0064	0.24	432.7 y	α 5486 keV (0.852) 5443 keV (0.128) 5388 keV (0.014) γ 60 keV (0.359)	Intake of plants, then inhalation and external
Sr-90	0.36	13	29 y	β^- 546 keV (1) (Y-90 64.1 h) β^- 2284 keV (~1)	Plant and meat intake

- Set Pathways
  - Uncheck Aquatic Foods
- Modify Data
  - Soil Concentrations
    - Bq/g and mSv/y, Basic Radiation Dose Limit 1 mSv/y
  - Contaminated Zone
    - Area 1×10^{15} m^2
  - Cover & Contaminated Zone Hydrological Data
    - Humidity 5.0 g/m^3
    - Average wind speed 2.5 m/s
    - Precipitation 0.5 m/y
    - Changed irrigation water to zero

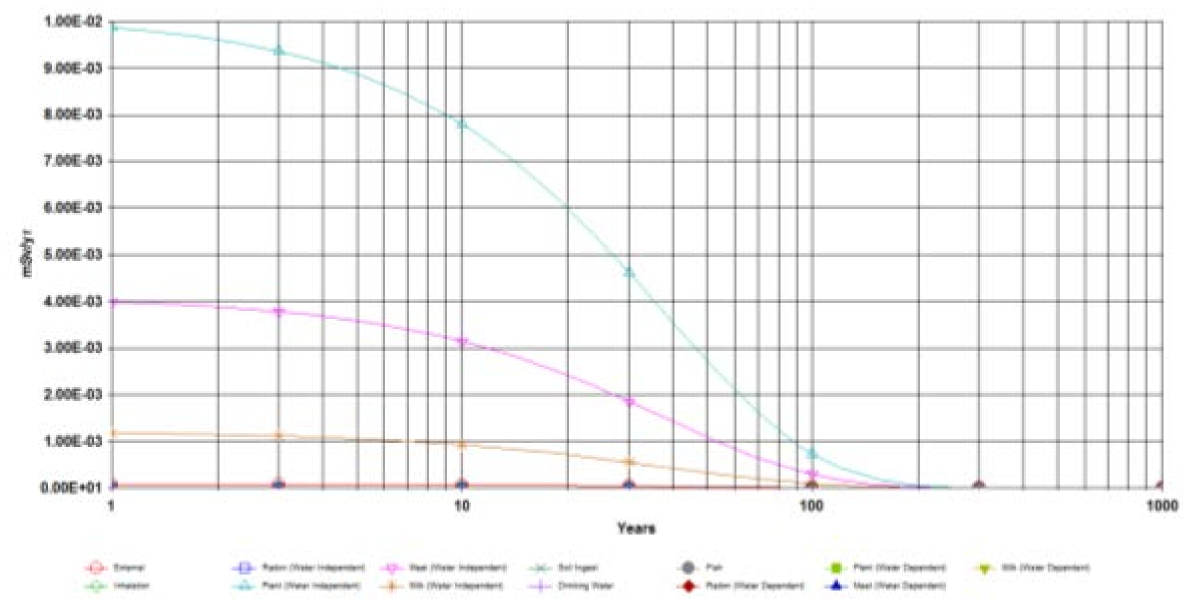
- Uncontaminated Unsaturated Zone Parameters
    - Changed unsaturated zone thickness to 300 m
- Occupancy, Inhalation, and External Gamma Data
    - Changed mass loading for inhalation to 0.00002 g/m^3 (20 µg/m^3) (100 µg/m^3 is too much particulate – can't see Jemez)
- Ingestion Pathway, Dietary Data
    - Irrigation water contaminated fraction set to zero
- Ingestion Pathway, Non-Dietary
    - Groundwater fractional usage for irrigation water set to 0

Results of Run: 0.026 mSv/y primarily from Sr-90 and Cs-137

DOSE: Cs-137, Component Pathways



DOSE: Sr-90, Component Pathways



View - SUMMARY.REP

File Edit Help

Font: MS LineDraw 7.4 Page: 17

RESRAD, Version 7.0 T½ Limit = 180 days 08/08/2014 14:15 Page 17
Summary : RESRAD Default Parameters
File : C:\RESRAD_FAMILY\RESRAD\7.0\USERFILES\FALLOUT.RAD

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mSv/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mSv/yr	fract.	mSv/yr	fract.	mSv/yr	fract.	mSv/yr	fract.	mSv/yr	fract.	mSv/yr	fract.	mSv/yr	fract.
Am-241	1.443E-06	0.0001	1.746E-06	0.0001	0.000E+00	0.0000	4.281E-06	0.0002	8.773E-08	0.0000	5.003E-09	0.0000	1.337E-06	0.0001
Cs-137	8.188E-03	0.3113	4.718E-08	0.0000	0.000E+00	0.0000	7.484E-04	0.0284	1.309E-03	0.0498	4.275E-04	0.0163	5.886E-06	0.0002
H-3	0.000E+00	0.0000	4.096E-05	0.0016	0.000E+00	0.0000	9.828E-06	0.0004	3.008E-06	0.0001	2.594E-06	0.0001	7.592E-10	0.0000
Pu-238	3.589E-09	0.0000	1.628E-06	0.0001	0.000E+00	0.0000	3.982E-06	0.0002	1.632E-07	0.0000	2.327E-09	0.0000	1.244E-06	0.0000
Pu-239	2.512E-08	0.0000	5.048E-06	0.0002	0.000E+00	0.0000	1.232E-05	0.0005	5.050E-07	0.0000	7.202E-09	0.0000	3.850E-06	0.0001
Sr-90	8.492E-05	0.0032	1.533E-07	0.0000	0.000E+00	0.0000	1.013E-02	0.3852	4.090E-03	0.1555	1.215E-03	0.0462	1.063E-05	0.0004
Total	8.275E-03	0.3145	4.958E-05	0.0019	0.000E+00	0.0000	1.091E-02	0.4148	5.404E-03	0.2054	1.645E-03	0.0625	2.294E-05	0.0009

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mSv/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mSv/yr	fract.	mSv/yr	fract.	mSv/yr	fract.	mSv/yr	fract.	mSv/yr	fract.	mSv/yr	fract.	mSv/yr	fract.
Am-241	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	8.900E-06	0.0003
Cs-137	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.068E-02	0.4060
H-3	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.639E-05	0.0021
Pu-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.023E-06	0.0003
Pu-239	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.176E-05	0.0008
Sr-90	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.553E-02	0.5905
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.631E-02	1.0000

*Sum of all water independent and dependent pathways.